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USES OF COLOR IN COMPLEX INFORMATION DISPLAYS

Cheryl A. Burnette

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USES OF COLOR IN COMPLEX INFORMATION DISPLAYS

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FOREWORD

This report summarizes human factors research concerning the impact on operator performance of the use of color in displays. It is intended for display researchers and design engineers as a general review of relevant research in experimental psychology and human factors.

The findings have been organized into several major sections. Basic attributes and phenomena of color perception are reviewed in the first section, along with some more complex perceptual effects. This section has attempted to provide display design guidance based on research in color perception and physiology. The next section highlights the primary ways that color can enhance operator performance. Although these fundamental uses of color provide general design guidance, more specific applications have been discussed in the section entitled Color and Task Performance. In this section, the impact of color has been summarized for perceptual, selective attention, cognitive, and psychomotor tasks. Additional considerations for the use of color, such as character size, ambient lighting, and visual fatigue, have also been reported. Finally, recommendations for using color, for selecting colors, and for enhancing symbol recognition are provided.

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SUMMARY

Problem

Current design plans for advanced submarine combat control systems include the use of high resolution color CRT displays. These displays are integral to complex tasks which require rapid assimilation of large amounts of data. Color coding is under consideration as a means of improving task performance and reducing operator workload.

Objective

The relevant human factors research literature was reviewed in order to establish guidance for the use of color in CRT displays in the submarine combat control environment.

Approach

Relevant research on the application of color to information displays was reviewed from several fields including visual physiology and psychophysics, experimental psychology, human factors and task performance, visual optics, color display technology, and ergonomics. This review included studies of the parameters affecting symbol legibility, such as character size, ambient lighting, display luminance, and symbol/background luminance and chrominance contrast. Functional characteristics of self-luminous displays, such as display polarity, were examined for their effects on symbol recognition. Finally, environmental factors (viz. ambient lighting, chromatic lighting and glare) and individual differences in perceptual ability and color preference were examined.

Findings

1. Effective display design requires consideration of the physical and psychological factors which affect color perception. Dominant wavelength, purity and luminance, symbol size, ambient lighting, background chrominance and luminance, distribution and functionality of the color receptors, various optical aberrations, retinal imaging, and retinal position all influence color perception. Second-order variables, such as luminance contrast and chrominance contrast, become important as additional colors are presented in the foreground or background.

2. The influence of these factors is complex due, in part, to the nonlinearity of the human response to color and to the differential sensitivity of the eye to light of different wavelengths. Even with equal luminance, some colors appear brighter than others. The eye is most efficient from the intermediate to the longer wavelengths (green to red). With

moderately high luminance and small symbol size, acuity is poorest for blue and highly saturated reds; the best acuity is achieved for yellow, yellow-green, orange, and green.

3. Luminance contrast is the most important factor in the detection of edges and borders. In the absence of luminance contrast when two display areas differ only in hue, the resulting border will be most indistinct when the two display areas differ only in the amount of blue cone stimulation. More distinct borders will be produced when the display areas differ in the amount of red and green receptor stimulation.

4. Color shifts, which are experienced as optical illusions, color reversals or shadows surrounding a symbol, may be induced by the luminance and chrominance contrast of nearby symbols. These shifts characteristically take place more readily for small symbols in larger backgrounds and for opponent-color combinations (e.g., red-green, blue-yellow).

5. Saturated colored symbols widely separated in wavelength (particularly blue and red) may appear to move or "float" when viewed on a field of another color of high saturation. They may also appear to either recede or advance from the background field. This optical illusion is known as chromostereopis.

6. Acuity and color perception are unreliable for symbols having less than 5 minutes of arc visual angle. Smaller symbols are perceived as being less saturated and less bright than larger symbols. For symbols fixated in the center field, sensitivity to wavelength, purity, and luminance increases with field sizes up to about 10 degrees of visual angle.

7. Visual acuity increases as the level of ambient light increases (to approximately 10 cd/m^2), and remains fairly constant over a wide range (from 10 cd/m^2 to 100,000 cd/m^2). At very high levels of ambient lighting, symbols will appear desaturated. Under very low ambient lighting (below .1 cd/m^2), blue is detected most rapidly and low saturation red least rapidly. However, actual acuity for blue symbology is poor, since there are fewer foveal cone receptors for blue.

8. The most effective applications of color generally involve its use: (a) to designate broad categories of information or specific important classes of data, (b) to aid in search and location, especially in the presence of visual noise, (c) to signal an alert to the operator to a need for immediate action, (d) to aid selective attention by highlighting or accenting important, or low probability information, (e) to aid short-term retention of category occurrence, size, or spatial location, (f) to provide scenic or pictorial realism, and (g) to enhance depth perception.

9. Research indicates that color is attended to and influences task performance even when it is irrelevant to the task at hand. Color is such a dominant cue that it can inhibit discrimination based on other coding dimensions.

10. Colored background patterns can disrupt efficient scan of a display. The use of colored borders and lines can also interfere with search by requiring the operator to process this information.

11. Research has consistently demonstrated that color is effective in improving performance in tasks requiring search for a target in high density displays. In fact, color has been shown to be more effective in enhancing search than other coding dimensions (viz., size, shape, or brightness). Since search time increases slightly as a function of the number of irrelevant colors on the display, it becomes important to reduce the color set size to as few colors as possible. One exception may be color coding on maps, where many colors may be used as long as color code information is available for reference.

12. Color is effective in tasks requiring absolute identification of information only when it is used in combination with alphanumeric labelling. A combination of color and alphanumerics is more effective then alphanumerics alone. For more than eight or nine categories of information, shape coding is more effective than color coding since there are more absolutely identifiable shapes than colors.

13. Color facilitates counting, especially in dense displays with small symbol size and few information categories. For reading, color is of no general advantage over black and white, except in highlighting text. Research has shown that many colors may provide adequate readability (except for highly saturated red and the shortest wavelengths - blue to purple) providing luminance and color contrast are good. Slightly desaturated spectral hues and mid-spectral moderately desaturated hues provide best readability for long-term viewing.

14. For complex tasks, color provides maximum benefit when the operator is required to search for information under conditions of high workload and high symbol/information density. Color is also useful for coding important information which occurs intermittently or in variable locations.

15. There are numerous ways in which color may be used to aid performance in complex tasks, such as monitoring, watchkeeping, inspection and surveying.

Recommendations

1. The following standards should be considered when selecting colors for use in complex, combat control information displays.

a. Colors used should be those maximally discriminable to the human observer, i.e., are sufficiently separated in wavelength to eliminate the possibility of confusion.

b. Colors should be maximally discriminable (have adequate color and luminance contrast) from the display background.

c. Colors should be related to the display in accordance with their conventional meanings (e.g., as red for "danger" or "tactical alert").

d. Colors used should be those that can be produced efficiently on the selected display.

e. Colors should be discernable under a wide range of lighting conditions.

f. Colors should provide high legibility.

g. Colors should not produce display or visual anomalies.

2. Under conditions of variable or uncontrolled ambient lighting, all colors, except red, should be selected at highest saturation levels (having a narrow wavelength), high luminance values and high color contrast between symbols and background. Maximal contrast between symbols and background can be achieved by using highly saturated, high luminous colors on a black, nonluminous background.

3. Under conditions of fixed ambient lighting optimized for task performance, dark characters on light backgrounds may be used. Visual fatigue during long-term task performance may be reduced somewhat by using dark character displays. These displays produce more direct glare, but less reflected glare and greater compatibility with printed material.

4. When using color to highlight text, avoid highly saturated red and the shortest wavelengths - blue to purple. Slightly desaturated spectral colors and middle wavelength mixed spectral colors provide best readability for long-term viewing.

5. Whenever color is used for coding critical items, it should be redundantly coded with an achromatic code, such as alphanumerics or shape.

6. Symbols should be coded at much higher brightness levels than the background. Symbol/background luminance contrast ratios of 10:1 are recommended for optimum visibility on multi-colored CRTs and on all displays requiring rapid response to signals. The minimum acceptable symbol/background luminance contrast ratio is 5:1.

7. To eliminate color confusion, it is recommended that only the minimum number of colors be used on the display. These colors should be as widely spaced as possible in wavelength, with a minimum color difference of 40 CIELUV units. No more than four or five colors should be employed on a display. If the task requires absolute identification of targets at the 100 percent level of accuracy, then a maximum of four colors should be selected.

8. The number of symbols coded in each color should also be kept to a minimum, and the same colors should be used for coding information across all displays.

9. Under good viewing conditions, satisfactory legibility is obtained for characters of a minimum size of 16 minutes of arc. To avoid confusion of colors, as the number of colors employed on the display increases, the minimum size of alphanumerics must also increase.

10. To provide for adequate display visibility under all ambient lighting conditions, it is recommended that display formats be planned for maximum visibility under the least favorable viewing conditions anticipated. If ambient lighting is variable, colors maximally separated in wavelength will be more discriminable under degraded lighting conditions.

11. For maximum visual acuity, the general level of white ambient lighting should be similar to that used on the display. If the ambient lighting conditions are variable, then the operator should be able to adjust display brightness. Display hoods are effective in reducing incident ambient light.

12. The interactions of display characteristics and chromatic illumination are complex and unpredictable at times. Strong colored ambient lighting may cause color shifts in display symbology. If chromatic illumination is to be used, it should be tested in the work environment.

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INTRODUCTION

Problem and Background

Advances in display technology have made it feasible to introduce high resolution, multicolor displays into the design of new submarine combat control systems. These systems typically require rapid assimilation and utilization of large amounts of data to support complex tasks such as fire control and sonar signal identification. There is concern that during periods of stress and increased workload, operators may become overburdened by the complexity and amount of the displayed information, resulting in degraded performance.

Color is being considered as a means for enhancing operator performance and reducing workload by improving combat information displays. Research findings from human color perception and human factors studies form the basis for the application of color to these displays. If the principles yielded by this research are not followed, color is unlikely to provide the desired performance benefits. In fact, nonjudicious use of color can distract, interfere with, or otherwise impair complex human information processing. Thus, there is a need to identify human factors guidelines for the uses of color in combat information displays.

Objective

The relevant human factors research literature was reviewed in order to establish design guidance for the use of color in combat control displays. This report is intended for designers concerned with the application of multicolor visual displays to complex information systems.

APPROACH AND ORGANIZATION

A research review was performed to determine the impact of color on operator performance in complex work environments, such as combat control. First, a computerized search was performed using numerous files from the National Technical Information Service database, the Lockheed Dialog System and the Defense File. The principal areas searched were: color perception, color coding, visual/computer displays, and specific applications of color to radar, sonar, weather and military mapping, combat control systems, avionics and air traffic control. The computer search spanned the years 1965 to 1984 and yielded 457 relevant articles and reports, including many review articles. The literature proved to be diverse, multidisciplinary and multinational in origin. Several review publications were found to be of particular value to the display designer (Derefeldt, 1981; Home, 1983; Silverstein & Merrifield, 1984).

Additional technical reports and journal articles from a not covered by these computerized databases were also ident This search was multidisciplinary, covering relevant resea computer graphics, display technologies, human factors, ergono visual physiology and psychophysics, applied optics, experim psychology, and avionics. In addition, the most current find were obtained through personal communication with recogn experts.

It is inappropriate to consider color usage as an isolat parameter. Color is normally used to code alphanumerics o specific symbology. Further, the value of color is maximized b the use of symbology appropriate to the task and by optimal display formatting. Accordingly, relevant work on symbol legibility, ambient lighting, display luminance and other factors important for performance using video display terminals was also reviewed.

It should be noted that most of the research published before 1975 used projected surface colors or incandescent signal lights rather than self-luminous displays. Similarly, much of the research comparing monochrome and chromatic displays is of little direct relevance, since prior to about 1981, monochrome displays necessarily offered much higher resolution than chromatic displays. For this review, special effort was made to locate recent research using very high resolution emissive color displays, particularly raster scan, shadow-mask and beam penetration CRTs.

As a context for determining the impact of color on task performance, a basic taxonomy of human skills was selected. This taxonomy of human skills (adapted from Alluisi, 1969) includes: (1) perceptual functions, such as detection and identification of signals, (2) attentional functions, such as search, monitoring, inspection, watchkeeping and surveying, (3) higher-order intellectual functions, such as counting, reading and decision making, and (4) psychomotor functions, such as aligning and tracking.

Performance characteristics of self-luminous displays which influence the identification and interpretation of colored symbology were also reviewed. Important here are factors of legibility and readability, polarity and achievable contrast ratios, and environmental factors, such as ambient lighting and glare. Individual differences in response to color have also been considered here. A glossary of basic terms is included for reference.

FACTORS AFFECTING COLOR PERCEPTION

Basic Color Attributes and Phenomena

Color is the perceived property of an object which results from the visual analysis of spectral light energy reflected from

an object's surface. The eye is sensitive to this spectral light in the range from approximately 380 to 750 nanometers. Within this range, the color of light is related to the spectral power or relative energy emitted at specific wavelengths. For example, blue is perceived at wavelengths below approximately 480 nanometers, green between 480 and 560 nanometers, yellow between 560 and 590, orange between 590 and 630, and red at wavelengths greater than 630 nanometers.

The three fundamental attributes of light, dominant wavelength, luminance, and purity, correspond to the perceptual attributes for the observer: hue, brightness and saturation. These perceptual attributes are interrelated, such that changes in any one attribute will modify the perception of the other two. For example, the perceived brightness of a light, although primarily a function of its luminance, is also a function of its wavelength. The dependence of brightness on hue results from the differential sensitivity of the eye to light of various wavelengths. When equated for luminance, light of different wavelengths will be perceived at different brightnesses.

Similarly, perceived hue is a complex function of both wavelength and luminance. This relation, known as the Bezold-Brucke effect (Wyszecki & Stiles, 1967), is most apparent at very high levels of ambient lighting, when hues appear desaturated. Some hues, for example, reds, will appear more desaturated than others under high ambient lighting.

A change in the luminance of a chromatic symbol affects both its perceived hue and saturation (Farrell & Booth, 1984; Silverstein, 1982). For wide ranges of luminance values, increased target luminance results in increased perceived saturation and improved color perception.

There is also a complex interaction between the perceptual attributes of color and the size of the perceived object. In general, the interdependence of hue, saturation, and brightness is more pronounced for symbols having less than 10 degrees of visual angle. For example, in order for small symbols to appear equally bright, desaturated symbols must have higher luminance than saturated ones. This is true for all wavelengths, except spectral yellow (Chapanis & Halsey, 1955).

While the scientific database remains incomplete, there has been considerable research to identify and explicate the various factors that influence color perception. These include: hue, saturation, brightness, symbol size, ambient lighting, background luminance, state of accommodation of the eye, distribution and functionality of the color receptors, light diffraction by the lens, pupil, and iris, various optical aberrations, retinal imaging, and retinal position. In addition, higher order cognitive factors, such as attention and

memory, are known to exert a significant influence on color perception.

As indicated, complex interactions exist for the perception of a single color. Second order variables, such as luminance and color contrast become important as additional colors are presented in the foreground and/or background.

Visual psychophysics is that branch of psychology that seeks to establish the relationships between the physical and psychological attributes of visual stimuli. Most psychophysical research on color perception has been conducted in controlled laboratory conditions using narrowly specified parameters of wavelength, purity, and luminance. However, general principles have been identified, many of which have important implications for chromatic display design. These principles are noted in boldface type below.

<u>Wavelength</u>

The most important effects of wavelength are discussed below. Summary statements are also provided for findings that are particularly relevant to display design.

> **The eye is most efficient at the intermediate and longer wavelengths, green to red.**

The fovea is primarily composed of the sensory receptors called cones, which are more receptive to the longer wavelengths (red and green) than to the shorter wavelengths (blue). In the primate fovea, approximately 57 - 67 percent of the cones are green-sensitive, 30 - 40 percent are red-sensitive, while only about 3 percent are blue-sensitive (Marc, 1977). Moreover, for light of shorter wavelengths there are increased diffraction effects (chromatic aberration) and some increase in the amount of light scattered in the retina (Boettner & Wolter, 1962; Kinney, 1967). Thus, the eye's efficiency and the range of color perception available in the green to red region exceeds that for the blue to green region (Murch, 1983a).

> **Above approximately 10 cd/m^2, acuity is poorest for blue and highly saturated red illuminants.**

Pokorny, Graham, and Lanson (1968) investigated the relationship between acuity and luminance for narrow-band chromatic red, yellow, green, and blue illuminants (at 650, 580, 530 and 460 nanometers, respectively). For four of five observers tested, acuity (measured as the ability to detect distance separations between wide and narrow vertical lines) was less for blue than for other spectral illuminants. This is found for both intermediate (1 to 100 trolands) and for high

luminance levels (beyond 100 trolands). One observer also showed lower acuity for red at high luminances.

Ferree and Rand (1931) measured acuity as the ability to judge orientations in the openings of broken circles for matched luminance spectroscopic light of varying wavelength. Results clearly showed lower acuity for red and blue illuminants than for those in the middle of the visible spectrum. For a low intensity light stimulus (.075 fc) the rank order of acuity from highest to lowest was: yellow (578 nanometers), yellow-green (563 nanometers), orange (624 nanometers), green (522 nanometers), red (666 nanometers), blue-green (501 nanometers), and blue (488 nanometers). The same rank order of acuity was obtained with a higher intensity light stimulus (.312 fc), although the colors blue and blue-green were not tested.

Schwarz (cited in Pokorny, et al., 1968) presented illuminants of high spectral purity and measured visual acuity as the ability to detect small openings in letters, Landolt C's, and Landolt broken circles appearing in various orientations. Acuity for extreme blue and red illuminants was inferior to that for wavelengths in the middle of the spectrum. Additional research with Landolt C-rings (Myers, 1967) showed that if perception of detail is required, blue is unsatisfactory for symbols of 2.5 minutes or less visual angle.

Brindley (1954) demonstrated that at low luminances, human cone receptors for blue are less active for stimuli having less than 7.5 minutes of arc. Wald (1967) verified this result, also finding that field sizes of 7.5 minutes of arc or less resulted in an inability to detect blue.

Numerous researchers have cited possible causes for reduced acuity for blue illuminants. Pokorny, et al., (1968) suggest dioptic (or refractive) scatter of light and/or fluorescence of the optic lens as well as retinal and neural factors. Kinney (1967) also cites effects due to chromatic aberration (diffraction effects caused by the varying focal length of light) and increased diffraction for the shorter wavelengths by the lens and iris. Confirming these explanations, Boettner and Wolter (1962) found increased light scattering in the optic media for the shorter as opposed to longer wavelengths. However, this increase was only of the order of 5 percent.

Relative to green or red, there are few blue receptors in the central fovea (Shlaer, Smith, & Chase, 1942). Thus, the fovea is considered to have the characteristics of a tritanopic (blue-blind) form of color blindness (Wald, 1967). These tritanopic effects are more apparent for tasks requiring direct fixation of symbols, such as in reading, than for tasks requiring continuous scan of a display (Halsey & Chapanis, 1954).

The normal eye is myopic for light of short wavelengths (blues); that is, in the absence of accommodation (focusing) action by the lens and iris, blue light will be focused prior to reaching the retina (Duke-Elder, 1946). However, for closer than normal viewing distances, blue is a satisfactory color to use[1].

Purity

Spectral purity is an important factor in color perception. A color consisting of light of a single wavelength is considered to be spectrally pure and maximally saturated. Spectral purity affects perceived brightness and plays a part in the perception of symbols on a surround.

> Increasing the saturation of a color increases its perceived brightness.

This effect has been reported by Farrell & Booth (1984) and by Pitt and Winter (1974). In general, the more saturated a color the brighter it will appear.

> The perceived saturation of a background field affects the perceived saturation of a symbol on that field and vice versa. However, the perceived saturation of the larger area will have greatest effect on the perceived saturation of the smaller area.

> Colored targets generally appear more saturated when presented against a light background than against a dark background.

This finding has been reported by several authors including Burnham, Evans, and Newhall (1952), Hunt (1950), and Pitt and Winter (1974). Using stimuli consisting of a mixture of red, green, and blue light presented against light and dark backgrounds, Pitt and Winter (1974) demonstrated that a dark background caused colored symbols to appear appreciably less saturated than when viewed against a light surround.

Luminance

The human eye is extremely sensitive to luminance, and it discriminates luminance levels over a wide range (Hurvich, 1981). Luminance is an important factor determining the perceived hue and also has profound effects on acuity.

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[1]Rupp, B. A. (September 1984). Personal communication. San Jose, CA: International Business Machines Corporation, Human Factors Center.

> **Threshold acuity and identification accuracy appear to increase with symbol luminance up to about 10 ft-L. Beyond 10 to 20 ft-L, there is little improvement in symbol identification.**

Display symbol luminance should be at least 10 ft-L. For most applications, a maximum symbol luminance of 20 ft-L is adequate (Shurtleff, 1980).

> **The eye has differential sensitivity to the luminance of light at various wavelengths.**

The amount of light energy necessary to be detected varies as a function of wavelength with the least amount of radiant energy necessary for threshold detection at 554 nanometers (yellow-green) (Hecht & Hsia, 1945). Even at suprathreshold levels, spectral illuminants of equal luminance will not appear equally bright to the observer. For example, in order to appear equally bright, the luminance of red light must exceed that of green light (Cakir, Hart, & Stewart, 1980).

<u>Luminance Contrast</u>

There are numerous definitions of luminance contrast in the literature. As one example, percent luminance contrast for an isolated target and background is defined as $[(L_1 - L_2)/L_1] \times 100$, where L_1 and L_2 are the respective luminances of the contrasting areas and $L_1 > L_2$ (Krebs, Wolf, & Sandvig, 1978).

The human eye is primarily dependent upon the detection of luminance differences to distinguish the borders between objects and the contours of a single object. The eye is particularly sensitive to the luminance contrast occurring between two objects or between an object and its background. In this manner, the retinal receptors serve to detect edges and borders between luminance of two different levels. The discriminability of a border is enhanced if two objects differ in luminance rather than only in hue.

> **Acuity is greatest for high target/background luminance contrast and for sharp edge definition.**

This issue has been addressed by Foley-Fisher (1977). Also, Guth and Eastman (1976) measured visual acuity as a function of luminance contrast for light and dark symbols on varied backgrounds. For low luminance contrasts of less than 20 percent, visibility was best for dark stimuli on light backgrounds.

Increasing the luminance of the background or surrounding area decreases the apparent brightness of the target.

The luminance of a large area has the greatest effect upon the perceived brightness of a small area. If the target symbol is large, increasing target luminance will decrease the perceived brightness of the background (Purdy, 1935).

A small target of fixed luminance appears to darken when the background luminance is increased (cf. Home, 1983).

Chrominance Contrast

The perceived color of a display symbol is affected by the color of its surround, including that of nearby symbols. Towards understanding these ef ts, a brief description of the predominant theory of human color vision is included. More detailed discussions of theories of color vision are provided in several texts (e.g., Boynton, 1979; DeValois & Jacobs, 1984; Wyszecki & Stiles, 1967)

According to current theory, human color vision is considered to be trichromatic and based upon an opponent-process mechanism (Boynton, 1979). In particular, the perception of color is mediated by three different types of cones each of which contains one of three different photopigments. These photopigments are maximally sensitive to wavelengths of 415, 535, and 567 nanometers (Bowmaker, Dartnall, & Mollon, 1980). The three types of receptors may operate independently but their photopigments have overlapping spectral bandwidths. Color perception is partly determined by the proportions of incident light that are absorbed by the three photopigments. The receptors respond to changes in the amount of light absorbed by the photopigments in a graded manner by depolarizing for decreases in luminance and hyperpolarizing for increases in luminance (Baylor, Lamb, & Yau, 1979).

This depolarization and hyperpolarization of the receptor cells produces changes in the activity of neurons in the retina and in the central nervous system that result in the perception of color. The prevalent theory of color vision (Boynton, 1979) proposes that colors are encoded by three opponent systems: luminance, blue-yellow, and red-green. These opponent systems, respond to the receptor signals differently. The luminance (or black-white) channel adds the signals from the red (567 nanometers) and green (535 nanometers) cones. The red-green process responds to the difference in the signals between the red and green cones. The blue-yellow channel responds to the

difference between the blue cone signals and the luminance signal. The neural mechanisms of these processes are not fully understood. However, considerable physiological research (reviewed by Lennie, 1984) has provided support for the opponent theory throughout the primate visual system.

Color shifts that are induced by the color of background or nearby symbols are presumed to be due in part to the opponent process mechanism. These shifts, typically manifest as shadows surrounding a symbol, optical illusions, and even color reversals may be detrimental to human color discrimination and judgment.

> **Colored symbols may appear to move or "float" when viewed on a field of another color of high saturation.**

This effect is hypothesized to be due to difficulties in accommodation (focusing or changes in the convexity of the lens to refract light to the retina) resulting from chromatic aberration within the eye (Home, 1983). Reducing saturation of the background reduces the effect (Home, 1983).

> **The color of small targets in bright backgrounds is shifted toward the complement of the surround.**

Hurvich (1981) and Silverstein (1982) have noted this effect in which, for example, a small, neutral colored target on a bright blue surround appears yellow. The greatest color shifts of this kind occur with small targets in large backgrounds. Conversely, the color of large targets is less dependent on background color (Graham, 1965).

> **Color shifts are strongest for opponent-color combinations: red-green and blue-yellow.**

Home (1983) recommends that opponent-color combinations be avoided for very small symbols on large backgrounds. Kinney (1967) found that color shifts for small symbols were more likely to be induced by blue backgrounds than by red ones.

> **Shadows may appear to surround a small target located in a field of the opponent color.**

> **Highly saturated colors, in proximity to one another, and sufficiently separated in wavelength, may give rise to distance illusions.**

This phenomenon, known as chromostereopsis, occurs most readily for the highly saturated colors of maximal wavelength

separation, red and blue. Highly saturated blues and reds may appear to recede or advance in space. In one study (Kraft, Booth, & Boucek, 1972), 50 percent of the observers reported that blues advanced while reds receded; 44 percent reported opposite movements. There were marked individual differences in the extent of the effects, but only 6 percent of the observers experienced no illusion. Hanson (1983) reported that while a few observers were fascinated by the illusion's sudden onset, most observers found it a distractive nuisance.

Chromostereopsis may be observed for other colors if they are sufficiently separated in wavelength. Adjustments in saturation may compensate for the illusion. For example, increasing the saturation of a color generally makes the object advance; decreasing the saturation generally makes it recede (Hanson, 1983).

The phenomenon of chromostereopsis is not well understood; however, its occurrence can be partially attributed to difficulties in accommodation which take place during near-simultaneous viewing of colors widely separated in wavelength.

> Luminance contrast has a much stronger influence on visual discriminability than does chrominance contrast.

The Eastman Kodak Company (1944) investigated the effects of luminance and chrominance contrast on visual acuity. The highest achievable chrominance contrast produced acuity equivalent to that with luminance contrast of approximately 35 percent. Guth and Eastman (1976) found that for luminance contrasts greater than about .40, increases in color contrast had little effect upon the visibility of an object. Taken together with the findings of Ludvigh (1941) in which luminance contrast of 34 percent resulted in high acuity, these findings suggest that small increases in chrominance contrast have less effect on acuity than small increases in luminance contrast up to 30 - 35 percent. Ludvigh's results also indicate that higher luminance contrast does not significantly change acuity. It should be noted, however, that luminance contrast for optimal acuity will vary somewhat as a function of symbol size, viewing distance, levels of ambient illumination, etc. Higher contrast may be necessary under degraded viewing conditions.

If two adjacent colors are equated for luminance, the border between them is somewhat indistinct. That is, if two adjacent colors differ only in hue, it is more difficult to perceive their border than if they differ only in luminance (Boynton, 1978). Moreover, the salience of the border between matched luminance objects varies with their wavelengths (Tansley & Boynton, 1978). For example, juxtaposed fields of red and green have a fairly sharp border; similar fields of blue and yellow tend to have very indistinct borders.

In general, luminance contrast plays a more important role in defining a sharp border between two areas than does pure chrominance contrast. However, one study (Cavonius & Schumacher, 1966) demonstrated that good visual acuity could be achieved for luminance-equated symbols and background if their chrominance contrast was sufficiently large (that is, the colors are sufficiently separated in wavelength).

> Chrominance contrast is perceived as maximal when luminance contrast is minimal (Kirshmann, 1891, cited in Butler & McKemie, 1974).

> With equal luminance for symbol and background, best chrominance contrast is achieved for moderately saturated backgrounds (Jameson & Hurvich, 1959).

> Chrominance and luminance contrast decrease with the spatial separation of the two interacting fields (Kirschmann, 1891, cited in Butler & McKemie, 1974).

> High luminance contrast reduces the perception of chrominance contrast. Equal brightness of symbol and background tends to maximize color contrast (Burnham, Hanes, & Bartleson, 1963).

Symbol Size

The size of a visual symbol critically affects acuity and color perception (Haines, 1975).

> Color perception is unreliable for symbols having less than 5 minutes of arc visual angle (Hunt, 1979). Even for normal observers, such symbols may appear shifted in hue or completely desaturated. A smaller symbol may be detected and identified, but its color may not be discriminable (Krebs, et al., 1978).

> Luminance and chrominance contrast detection thresholds depend strongly on symbol size. Very small symbols result in a decreased ability to perceive differences in brightness or chrominance contrast between the symbol and its background (Koenderink, Bouman, Bueno de Mesquita, & Slappendel, 1978).

For symbols fixated in the central field, sensitivity to wavelength, purity, and luminance increases with field size up to about 10 degrees of visual angle (Wyszecki & Stiles, 1967).

Low luminance decreases acuity, especially for small symbols. Larger symbols may be used to compensate for a decrease in luminance (Graham, 1965).

For two symbols of equal purity and luminance, the smaller one is generally perceived as being less saturated and bright than the larger symbol (Wyszecki & Stiles, 1967). Thus, it may be necessary to code very small symbols at higher levels of luminance and purity.

The smaller the target symbol and the larger the background or nearby color, the greater the luminance and chrominance contrast effect between them (Kirshmann, 1891, cited in Butler & McKemie, 1974).

Shifts in perceived color are most evident for small symbols on large backgrounds (Graham, 1965).

Ambient Illumination

Visual acuity increases as the level of ambient illumination increases to approximately 10 cd/m^2. Between 10 cd/m^2 and 100,000 cd/m^2, visual acuity is fairly constant.

Acuity declines for ambient illumination levels above 100,000 cd/m^2 due to glare from diffraction effects within the eye. In these extremely high ambient lighting conditions, symbols may appear completely desaturated and, in fact, achromatic (Laycock, 1982).

The short wavelength (blues) are detected more easily than the longer wavelength (reds) under very low levels of ambient illumination.

Pollack (1968) conducted a study comparing reaction time to detect the onset of light of 6 different wavelengths, equated at 5 levels of luminance (over a range of 5.2 log units with a

central value of 1 millilambert). At the lowest luminance level, more rapid response was made to the shortest wavelength (blue) light. However, even though blue light may be detected more readily under conditions of low lighting, the actual acuity for blue objects is poor, since there are fewer foveal cone receptors for blue (Shlaer, et al., 1942).

Under reduced daylight conditions (0.1 - 5.0 ft-L white tungsten illumination, and approximately 5 ft-L white fluorescent illumination), most errors in recognition occur for identification of low saturation reds (Feallock, Southard, Kabayashi, & Howell, 1966).

The level of ambient lighting at which the perception of color for the longer wavelengths is degraded varies as a function of symbol background size and color (Burnham, et al., 1963). Larger symbol sizes will be subject to less degradation under low ambient lighting.

FUNDAMENTAL USES OF COLOR

The questions most frequently asked by display designers regarding the use of color are: What is the most appropriate use of color? What items should be color coded? Can operator task performance be improved through the use of color? Some of these questions have been addressed directly by experimentation. Although most research findings are highly task specific, those considered to have more general value are summarized in Table 1 and in the following text.

Table 1

Summary of Basic Research Findings for Use of Color on Visual Displays

USE	APPLICATION
1. Designate broad categories of information or classes of data	a. to add meaning to the display or to increase the information capacity of the display b. to aid in locating specific color coded information in the presence of other information by reducing the need for visual search c. to designate broad categories of information which require alternate courses of action d. to standardize categories of information across displays
2. Alert the operator to a change in display status or to the need for immediate action	a. to reduce reaction time to important or critical information (when the color is known in advance) b. to key a particular response to a specific color c. to aid selective attention, by highlighting or accenting important, or low probability information
3. Aid short-term retention of category occurrence and size, and to aid memory for the spatial location of information	a. to reinforce memory for meaning of colored symbols due to correspondence to conventional meanings (brown for earth, blue for sky, green for vegetation)
4. Enhance pictorial displays by highlighting or scaling stimulus features	a. to provide scenic or pictorial realism b. to improve feature extraction capability c. to provide a greater salience of intensity variations than is possible with monochrome data d. to enhance image spectral depth e. to highlight or reinforce geometric cues

Classify

Using the task of the air traffic controller, Wedell and Alden (1973) had observers keep track of the identity and position of 6, 8, or 10 aircraft whose altitudes were coded either in color or in numerals. Numeric coding produced fewer errors, but color promoted the categorization of data and aided in the retention of information regarding category size and location of aircraft.

In a review article, Teichner, Christ, and Corso (1977) concluded that color is most useful to categorize broad classes of data, such as friendly versus enemy aircraft. More specific classes of data, such as aircraft type, should then be designated by shape or by letter. It turns out that color is most effective if there are few required categories (Smith & Thomas, 1964) and few items per category (Shontz, Trumm, & Williams, 1971).

Smith (1962) found that color coding improves discrimination and visual separation among items in a large display. The author suggested that if an item is color coded, its spatial location is more perceptible and its class is apparent at a glance.

In a series of ten experiments (Christ & Corso, 1975), the effects of alphanumeric, shape, and color coding were tested in the performance of simple tasks (choice reaction time, search and location, and multiple target identification). The results indicated that color was most useful for organizing information in complex, multiple stimulus formats.

Alert

Other research has demonstrated that color is useful to call attention to critical information. Luder (1984) required operators to perform a tracking task while monitoring color or monochrome displays located in the visual periphery. Results indicated that color aided the recognition of peripheral signals and also improved tracking performance. In this task, operators were not able to inhibit their processing of color attributes even when it was to their advantage to do so (i.e., when color was irrelevant or inappropriate to the task requirements). The author notes that since color produces a "perceptual de-emphasis" of other information, it should be used to code only the most important task information.

Aid Recall of Spatial and Category Information

Color has not proved generally useful as an aid to the retention or learning of instructional material (Craig, 1978; Pesenti, 1976; Whelply, 1979). However, it may aid in the

retention of data concerning size and spatial location (Wedell & Alden, 1973) and in the memory for the occurrence of a category (Clark, 1969). In a review article, Clark and Preston-Anderson (1981) state that color memory deteriorates less rapidly than memory for shape, orientation, or target size; however, no empirical data are cited as the basis for this assertion.

Kafurke (1981) examined the use of color-coded tactical symbology on military maps. Subjects were required to identify objects on the basis of color and to denote their locations on a copy of the displayed map. Ability to recall original location of the color coded information was superior to ability to recall shape coded information on monochrome displays.

In a visual recognition task, Kroll, Kellicutt, Berrian, and Kreisler (1974) asked subjects to respond "same" or "different" to a pair of letters presented sequentially with a retention interval of either 1 second or 8 seconds. When the two letters differed in color, response time was increased. The authors concluded that color requires processing time and is maintained as part of the visual memory image.

Feature Enhancement

Color can be used to highlight important status indicators or display parameters, to provide pictorial realism (such as brown for earth and blue for sky), to increase the number of possible intensity variations, to enhance image depth, or to highlight and reinforce geometric cues. Shading may also be used as a multidimensional cue to represent third order variables, such as acceleration.

Intensity or color shading (changes in the brightness, hue, or saturation of a color) may be used to indicate the range of a parameter value (such as the color coding of different hues on a thermograph). Color-shaded displays of three-dimensional geometries have been demonstrated to be a viable means of displaying range or higher-dimensional data (Applegate, 1981). Derefeldt (1981) recommends use of the hue dimension to code qualitative changes in information, and brightness and saturation to code quantitative changes. An example of this would be to use color to code threat type, and brightness to code intensity or age of threat information.

The value of color shading to represent intensity variations, depth or range data appears to be highly task specific and should be approached with caution. Changes in hue or saturation used to indicate the approach of a threat may distract the operator from the performance of critical tasks. There is also reduced acuity for moving symbols.

Brown (1971) investigated the effects of motion, or sequential changes in background colors during performance of a search task on a simulated radar display. Two sequences of background color change (red-green-blue and blue-green-red) and three rates of color change were investigated. Search rates were adversely affected by an increase in the rate of color change. Search times were longer for the blue-green-red color change sequence.

Wallace (1971) studied the effect of speed and sequence of background color change on accuracy of detection of simulated radar targets in noise. Results showed that homogeneous green or blue backgrounds enhanced target detectability when compared to sequentially changing colored backgrounds, and that speed (slow, medium, and fast) and sequence of change (red-green-blue or blue-green-red) had little effect.

Ineffective Applications

As noted previously (Kroll, et al., 1974), color requires processing time and is maintained as part of the visual memory image. Color, as one of the most salient features of an object, may be processed in the absence of full selective attention. Some research indicates that color is processed even when it is irrelevant to the task at hand (Luder, 1984) and inhibits discrimination based on other coding dimensions (Smith & Thomas, 1964). A study by Schroeder (Honor's thesis from the University of Oregon, cited in Posner, 1978) tested for "same" or "different" responses to simultaneous presentation of stimulus pairs that varied in shape or color. When the task was to determine whether the stimuli matched on the basis of color, response time was unaffected by irrelevant shape. However, when color was the irrelevant dimension, the response time for shape discrimination increased. Reinforcing this result, Long, Eldridge, and Carver (1982) note that when color coding is used, one must ensure that processing based on other coding dimensions is not adversely affected. Color information is difficult to ignore and irrelevant color can serve as a distraction to the operator, requiring additional processing time with no gain of useful information.

Color may enhance display organization if used to physically separate or group data sets. However, research (Cahill & Carter, 1976) indicates that the use of colored borders and lines intended to separate display regions may prove disruptive to search by requiring the operator to process irrelevant information. Similarly, background patterns may inhibit efficient scan of a display (Zwaga & Duijnhouwer, 1984).

It is more efficient to use color to provide meaningful information to the operator. If color is used to alert the operator or to convey important classes of information, then its

use in providing border lines or separation between parts of a visual display should be avoided.

It is more efficient to delineate areas of a display by spatial separation or, if necessary, to define essential borders by a color which is very similar to the background color. Luminance contrast is very effective in highlighting new or important information without the use of additional display colors.

COLOR AND TASK PERFORMANCE

Significant human factors research concerning color and task performance is summarized in Table 2. This table is intended as a quick reference for the engineer or display designer. Although simplified, this table provides general guidelines for the use of color in various types of tasks. For all tasks, it is assumed that accuracy and response time are of critical importance. Caution is advised in making inferences concerning the appropriate use of color, number of color categories, and optimal color characteristics for complex task performance based solely on data obtained from the simple tasks reviewed here.

TABLE 2

SUMMARY OF EXPERIMENTAL RESULTS
ON COLOR AND TASK PERFORMANCE

TASK	PRIMARY USES OF COLOR	CODING METHODS	MULTIDIMENSIONAL CODING	MAXIMUM NUMBER OF COLOR CATEGORIES	DISPLAY DENSITY CONSIDERATION	OPTIMAL COLOR CHARACTERISTICS
Detection	Increase salience of critical items	(1) Color (2) Shape (3) Alphanumerics				Maximum wavelength separation (Nissen, Pokorny, & Smith, 1979). Highly saturated colors produce fastest reaction times (Nissen, et al., 1979). Use red of dominant wavelength less than 640 nanometers (French Society of Ergonomics, cited in Rupp, 1981). Most highly saturated spectral colors produce similar response time (Pollack, 1968). Reaction time to red is 24 milliseconds faster than to green (Jones & Wilkerson, 1975). Colors having conventional meaning (red, yellow and green) predispose operator to respond in a particular way. Condition response to specific color.
Absolute Identification	Identification solely on basis of color is not recommended. Redundant color aids identification accuracy (Anderson & Fitts, 1958).	(1) Alphanumerics (2) Color for fewer than 8 or 9 categories. Shape for more than 8 or 9 categories (Smith & Thomas, 1964).	Identification based on multiple codes is more accurate than identification based on only one dimension (Eriksen & Hake, 1955). Up to 3 coding methods recommended for identification tasks (Eriksen, 1954). Identification is more accurate based on color than on size or brightness. (Eriksen & Hake, 1955). Joint use of alphanumerics and color yield superior	Only 4 colors identifiable at 100% accuracy (Teichner, Christ, & Corso, 1977). 4 colors identified with 90% accuracy for symbols of 17 min. of arc (Haeusing 1976).	For a small number of information categories, color superior to shape for high display densities (Christ, 1975). For low density displays use alphanumerics and spatial separation.	Maximum wavelength separation. Use of colors with conventional meaning may improve identification accuracy.

TABLE 2 (CONT.)

TASK	PRIMARY USES OF COLOR	CODING METHODS	MULTIDIMENSIONAL CODING	MAXIMUM NUMBER OF COLOR CATEGORIES	DISPLAY DENSITY CONSIDERATION	OPTIMAL COLOR CHARACTERISTICS
Absolute Identification (cont.)			identification than alphanumerics alone (Anderson & Fitts, 1958).			
Discrimination and Comparison	Increases visual separation of items	(1) Color (2) Shape (3) Alphanumerics		8 to 10 (for 97 to 100% accuracy) (Halsey & Chapanis, 1951; Baker & Grether, 1954; Halsey & Chapanis, 1954).		Least agreement among observers border colors between blue and g (Halsey, 1959). Narrow frequency for high accuracy recognition of True spectral green signals iden with high accuracy (97%). Violet purple confused with blue. Blue sionally confused with red, and confused with magenta. Blue and confused for symbol sizes of les 20 minutes of arc (Wilmer & Wrig 1945). Adequate visual separabil minimum recommended separation o CIELUV units to avoid color conf (Carter & Carter, 1981).
Search and Location	Reduces time necessary for search and location only when color of target is known.	(1) Color (2) Shape	Use of color and shape coding together will slow search (Schneider & Eberts, 1980). Color yields faster search than form, size or brightness (Eriksen, 1952).	7 to 9 highly discriminable colors (Cahill & Carter, 1976). 4 or 5 (Krebs, et al., 1978; Smith, 1962). More than 4 or 5 with availability of color code reference information (Williams, 1967).	For low density displays: 10 to 20 symbols) as many as 9 colors can be used with no increase in search time. For higher density displays (30, 40 or 50 symbols) up to 7 colors may be used with little or no increase in search time (Carter & Cahill, 1978). Color is most effective for few color categories (Smith & Thomas, 1964) and more items per category than for more color categories	

TABLE 2 (CONT.)

TASK	PRIMARY USES OF COLOR	CODING METHODS	MULTIDIMENSIONAL CODING	MAXIMUM NUMBER OF COLOR CATEGORIES	DISPLAY DENSITY CONSIDERATION	OPTIMAL COLOR CHARACTERISTICS
Search and Location (cont.)					and fewer items per color category (Cahill & Carter, 1976). Color more effective aid to search for high density displays (Smith, 1962). Homogeneous backgrounds improve search. If heterogeneous backgrounds are used, structure (e. g., rows) improves search (Farmer & Taylor, 1980).	
Monitoring and Watch-keeping	To reduce need for search and processing of irrelevant information. To code a master alert signal. To code low probability information. To aid in the maintenance of alertness.				With high display density, critical information should be located in standard display location, preferably upper right corner followed by upper left, lower right and lower left corner (Smith, 1978). Monitoring performance improves if display contains subsets of information rather than one homogeneous array (Kenerick & Petersen, 1971).	Adequate chrominance and luminance contrast between symbols and background will improve visual discriminability and separation of color (McLean, 1965).
Inspection	To highlight important status indicators. Use intensity or color shading to indicate range data or higher dimensional data. Use of hue dimension to code qualitative information changes and brightness and saturation to code quantitative changes (Derefeldt, 1981).					Slow rate of color change is preferable (Brown, 1971).

TABLE 2 (CONT.)

TASK	PRIMARY USES OF COLOR	CODING METHODS	MULTIDIMENSIONAL CODING	MAXIMUM NUMBER OF COLOR CATEGORIES	DISPLAY DENSITY CONSIDERATION	OPTIMAL COLOR CHARACTERISTICS
Surveying	To improve situational awareness. To aid recognition of information categories. To designate categories of information requiring immediate courses of action. To code status indicators. To enhance pictorial displays.					
Counting	Color facilitates counting (Christner & Ray, 1961; Hitt, 1961; Smith & Thomas, 1964).	Research comparing effectiveness of color and numeric coding is equivocal (Christner & Ray, 1961; Hitt, 1961).	Counting on basis of color is faster than on basis of shape (Christner & Ray, 1961).		Superiority of color versus shape coding increases with display density. Color especially useful for counting in dense displays with small symbol size and few information categories (Smith & Thomas, 1964).	Counting of blue symbols slower than for other colors (Smith, 1963b). Counting of blue and green slower than for red, white and yellow (Smith & Thomas, 1964).
Reading	Color no general advantage to black and white, except to highlight text.	Color coding used only when necessary to increase saliency of text.	Consider use of redundant code whenever visual acuity or legibility is degraded.	Few, due to high distraction of colored text.		Many colors (except for shortest wavelengths blue to purple) provide adequate readability providing luminance and color contrast are good (See footnote 2 in text). Middle wavelength mixed spectral colors may provide best readability for long-term viewing (See footnote 3 in text).

TABLE 2 (CONT.)

TASK	PRIMARY USES OF COLOR	CODING METHODS	MULTIDIMENSIONAL CODING	MAXIMUM NUMBER OF COLOR CATEGORIES	DISPLAY DENSITY CONSIDERATION	OPTIMAL COLOR CHARACTERISTICS
Complex Information Processing and Decision Making	To code information requiring search in high density displays. To code information which occurs intermittently or in variable location. Color relatively ineffective in complex tasks with fixed formats, highly legible symbols and low symbol density (Krebs, et al., 1978).	Select from alphanumerics, color, shape, brightness (bright and dim), and size.	Value of redundant code varies as a function of task. No more than 3 coding dimensions.	4 or 5 (Krebs, et al., 1978).	Color generally provides maximum benefit under conditions of high workload and high symbol/information density. Color provides maximum benefit for search tasks (Krebs, et al., 1978).	Determination in context of task to be performed. In general, color aids search, counting, and detection, if color of target is known in advance.
Map Reading and Reconnaissance	To reduce CRT display clutter. To differentiate classes of data on map backgrounds. To promote highlighting and enhance separation and classification of displayed data (Adams, 1978).	(1) Color (2) Shape		7 (Adams, 1978). 28 (with color code reference list as aid to memory) (Shontz, Trumm & Williams, 1968).	Color most effective when number of objects per color class is less than 11 (Shontz, et al., 1968).	Use colors highly discriminable in the visual periphery (Shontz, et al., 1968). Wide wavelength separation between colors. Adequate luminance and chrominance contrast between symbols and background (McLean, 1965).
Command-Control	To improve awareness of tactical situation. To decrease operator's response to work distractions. To enhance effectiveness of inexperienced					

TABLE 2 (CONT.)

TASK	PRIMARY USES OF COLOR	CODING METHODS	MULTIDIMENSIONAL CODING	MAXIMUM NUMBER OF COLOR CATEGORIES	DISPLAY DENSITY CONSIDERATION	OPTIMAL COLOR CHARACTERISTICS
Command-Control (cont.)	operators (Oda, 1977). To aid in interpreting overlapping or overprinted symbology. To alert operator to changes in tactical situation, to manage a high volume of complex data with multiple overlays. To differentiate targets from backgound. To indicate aging of information. To aid status monitoring. To delineate details in weather maps. To improve feature identification and image spectral depth (beyond that possible with monochrome displays). To correlate tabular data with graphical information.	Select from alphanumerics, color, shape, brightness (2 levels) and size.				
Peripheral monitoring performed simultaneously with control tasks	Reduces search time for peripheral displays and improves primary tracking performance (compared to monochrome displays) (Luder, 1984). Color does not aid absolute identification in peripheral displays (Luder, 1984). Peripheral color display (opposed to monochrome)		Joint color and shape coding superior to shape coding alone (Kopala, 1979). Color more readily identified in the periphery than shape (Peeke & Stone, 1973).	Fewer than 4, since colors must be in visual periphery.	Color most effective in reducing RT and errors for high density peripheral displays (Kopala, Reising, Calhoun & Herron, 1983). Increasing display density (from 3 to 9 elements) degraded search and identification per-	

TABLE 2 (CONT.)

TASK	PRIMARY USES OF COLOR	CODING METHODS	MULTIDIMENSIONAL CODING	MAXIMUM NUMBER OF COLOR CATEGORIES	DISPLAY DENSITY CONSIDERATION	OPTIMAL COLOR CHARACTERISTICS
Peripheral monitoring performed simultaneously with control tasks (cont.)	may aid in reduction of fatigue on primary tracking task performance (Luder, 1984).				formance for monochrome displays but did not affect performance on color displays (Luder, 1984).	

Perceptual Tasks

Stimulus Detection and Identification

Detection and identification of signals are a critical part of performance of many tasks. In detection, the observer reports the signal's onset; the dependent measure is response time, measured as the interval starting with the presentation of the signal and terminating in the observer's response. In identification, the observer must also indicate the particular type of signal; the accuracy of identification, as well as the response time, is recorded. Typically, detection and identification are coincident.

A number of studies have examined whether one color can be detected more quickly than another. Pollack (1968) compared the time to detect the onset of various colored lights. He tested six different wavelengths, equated at five levels of luminance. No differences were found in the time to detect any of the six wavelengths at the four highest luminance levels.

Jones and Wilkinson (1975) measured observers' reaction times to red and green lights. The reaction times to red lights were, on the average, 24 milliseconds faster.

Nissen, et al., (1979) instructed their observers to respond to six luminance-matched chromatic stimuli (460, 502, 542, 570, 613, and 650 nanometers) but to ignore white light. Fastest response times were obtained for the shortest and the longest wavelengths; the slowest response time was observed for light at 570 nanometers (yellow). Although this result may reflect detection performance as a function of wavelength, it may also have been due to perceived differences in saturation. At moderately high levels of equal luminance, colors near the ends of the visible spectrum appear highly saturated, while color at 570 nanometers appears least saturated.

Graham (1965) reported a study of a task requiring identification of luminance-matched red and green words and letters. Recognition of red words and letters was both faster and more accurate than recognition of green words and letters. Moreover, the relative benefit of red over green was greater with words than with letters. This was interpreted as a cognitive effect reflecting the conventional use of red to denote danger.

In a study conducted using a fighter aircraft cockpit simulator (Kopala, Reising, Calhoun, & Herron, 1983), pilots responded to real-time threat information presented on color coded or on black and white displays. This task was performed in addition to the primary one of flight maneuver. Threat

displays were coded either by achromatic shape symbology or color and shape coded symbology. In the experimental condition of interest here, the pilots needed only to identify the symbol type. Higher accuracy and faster response times were obtained for color coded versus achromatic displays. Furthermore, the advantages of color in reducing reaction time and errors increased as display density increased.

The effectiveness of color coding on visual displays has been compared to the achromatic coding methods of shape, brightness, size, and alphanumerics (Eriksen, 1952, 1953, 1954; Eriksen & Hake, 1955; Hitt, 1961; Hitt, Schutz, Christner, Ray, & Coffey, 1961). Eriksen and Hake (1955) asked observers to identify stimuli which differed from one another along 1, 2, or 3 stimulus coding dimensions: size, hue, brightness, and their combinations. Results showed that identification based on color was more accurate than identification based on size or brightness. Identification based on multiple stimulus coding dimensions was more accurate than identification based on any single dimension. Identification latency was not recorded.

In a similar study varying hue, brightness, and size, Eriksen (1954) found that identification based upon two and three dimensional codes was superior to that based upon any one dimensional code and that three dimensional codes were superior to two dimensional codes. When only one coding dimension was used, color codes were superior to size or brightness codes.

Research comparing color and other coding schemes to alphanumerics has shown that alphanumeric labelling is the most effective single coding technique to employ for rapid and accurate identification (Christner & Ray, 1961; Hitt, 1961; Mackworth, 1963; Wedell & Alden, 1973). In particular, the maximum amount of information conveyed by alphanumerics is far greater than that which can be conveyed by color. However, the joint use of alphanumerics and color transmits more identity information than alphanumerics alone (Anderson & Fitts, 1958).

Absolute identification based on color information alone is limited since only a few colors are reliably identified over a wide range of lighting conditions. Several authors (Teichner, 1979; Teichner, et al., 1977; Wagner, 1977) have recommended that a maximum of four colors be used to ensure that each color can be identified with 100 percent accuracy. If more colors are used, identification accuracy is likely to be reduced.

If the number of display information categories is small, color provides more identity information than shape (Allport, 1971; Mackworth, 1963). However, color transmits less additional information as the number of information categories increases (Smith & Thomas, 1964). If the number of information categories exceeds about eight or nine, shape transmits

information more efficiently, since there are more absolutely identifiable shapes than colors (Anderson & Fitts, 1958). Christ (1975) noted that for identification tasks having a small number of information categories, the relative superiority of color over shape increases as a function of increasing display density.

When both speed and accuracy of symbol identification are necessary, use of two coding methods is advised (Anderson & Fitts, 1958). With low density information displays, alphanumerics and spatial separation may be as effective as alphanumerics and color. For more than eight or nine information categories, alphanumerics and shape appear preferable.

A secondary, redundant code is also recommended whenever visual acuity or legibility is degraded. However, caution should be exercised since as the number of redundant coding dimensions increases, the inhibitory effect of the irrelevant symbology also increases (Jones, 1962). Thus, Laycock and Viveash (1981) suggest that no more than three coding methods be used in a single display.

Stimulus Discrimination and Comparison

Color coding is a very effective method of enhancing discriminability among classes of data (e.g., Green & Anderson, 1956; Smith, 1962). Estimates of the number of colors that can be reliably discriminated range from 5 - 12, with the exact number dependent upon the specific viewing conditions (Conover, 1959; Halsey & Chapanis, 1951). In order to maintain a very high level of discrimination accuracy (97 - 100%), only eight or nine colors should be employed (Baker & Grether, 1954; Feallock, et al., 1966).

Several studies have attempted to determine the perceptual boundaries between colors and to predict the extent to which confusions occur. In an important example of this research, Halsey (1959) investigated the perceptual boundaries of projected colors (green, blue, white and purple) for untrained observers. The stimuli were small, low luminance signal lights, for which luminance was varied across hue to create equal brightness stimuli. One hundred observers were required to identify 50 test stimuli exposed for 2 seconds each. There were wide individual differences in the naming of colors, with the least agreement among observers for colors near the boundary between blue and green. At low luminance, more violets were named as blue, and there was poor identification of borderline colors of blue, green and purple. The observers visual acuity (normal vs. abnormal) had no effect on color naming. Green signals were identified with a high level of accuracy (92%), although, as noted before, there was some confusion among blues

and short wavelength greens. The frequency band for high accuracy recognition of blue was very narrow. Purples were occasionally confused with red. Halsey suggested that blue and purple should generally not be used in the same color coding system unless their use is severely restricted. With yellow lights in the background, whites and yellows were frequently confused. With blue and green lights in the background, there were very few instances of confusion between either blue and white or green and white.

Willmer and Wright (1945) investigated visual acuity as a function of symbol size and color. Results showed that subjects were unable to reliably discriminate blue from green for very small test fields (20 minutes of arc or less).

In a color-naming task using CRTs under high ambient lighting (8000 fc) and symbol sizes of 20 minutes of arc, Silverstein and Merrifield (1981) found poor acuity for purple, and a disproportionately high number of confusions between green and cyan, and between red and magenta (the latter was ameliorated by shifting magenta slightly closer to blue along the red-blue chromatic axis).

An early study by Halsey and Chapanis (1954) using signal lights sought to identify colors that were least likely to be confused. They found eight colors that were discriminable with 97.5 percent accuracy. Fairly simple names could be assigned: orange, yellow, green, white, greenish-blue, violet, pink, and reddish-purple.

Halsey and Chapanis (1951) asked observers to assign names to hues which were presented one at a time. Results showed that 10 hues could be identified 97.5 percent of the time, and 17 hues could be identified correctly 72.4 percent of the time. The wavelengths selected were: 430, 476 (blue), 494, 504, 515 (green), 556, 582 (yellow), 596, 610, and 642 (red) nanometers. In an experiment using only one observer, Hanes and Rhoades (1959) found that with extended practice over five months, 50 different colors could be identified with almost perfect accuracy. However, this capability declined rapidly upon cessation of practice.

Green and Anderson (1956) and Smith (1962) concluded that adequate visual discriminability is provided by a code of four or five colors; that is, search for a target of one color in the presence of three or four other colors is almost as rapid as search for that target on a monochrome display. These experiments examine a maximum of only five colors.

Haeusing (1976) investigated the discriminability of colors on raster scan CRTs as a function of symbol size. For color symbols subtending at least 45 minutes of arc and presented one

at a time, there were six color regions which could be discriminated at least 90 percent of the time: red (599 nanometers), green (548 nanometers), cyan (520 nanometers), yellow (582 nanometers), blue (578 nanometers), and purple (516 nanometers). For symbols of less than 30 minutes of visual arc, only five equivalent color regions provided discriminability at 90 percent accuracy: red, green, blue, purple, and yellow. For symbols of 17 minutes of arc, only four color regions provided discriminability at 90 percent accuracy: red, green, blue, and purple.

Williams (1966, 1967) conducted a search study using eye movement data and found that the ability to discriminate among colors does not deteriorate when the number of colors is increased as long as the observer is given reference information concerning the relationships conveyed by the color code. In the absence of reference information, observers apparently had difficulty remembering the relationships conveyed by the color code, and retrieval of these was a significant factor affecting overall search times. The author suggested making color code information readily available for reference during search.

Shontz, Trumm, and Williams (1968) used multiple colors to code checkpoints on aeronautical charts. Observers were asked to locate specific map checkpoints on the basis of sketch cards representing object and terrain features observed from a cockpit. Maps contained various numbers of background colors (7, 14, and 28) and lines, and were sorted into four groups: few colors-few lines, few colors-many lines, many colors-few lines, and many colors-many lines. Results showed that when color code information was available for reference during search, up to 28 colors could be used effectively. Color coding was also found to be useful for locating of information on maps when colors are highly discriminable in the visual periphery and the number of objects per color class is less than about 11. When the color coding system used for aeronautical charts was superimposed on terrain elevation maps using another color code system, the overlay did not adversely affect target location performance.

Selective Attention Tasks

Search and Location

A common task involves the search for selected data embedded in other information. Here the operator is required to locate (or simply declare the presence/absence of) a particular symbol or class of symbols on the display. Search is distinguished from detection in that it always requires eye movement.

If search time is critical, coding the information by size, shape, or color is frequently used to aid discrimination and thereby to facilitate the search process. Indeed a consistent finding (e.g., Christner & Ray, 1961; Green & Anderson, 1956;

Smith 1962) is that color coding reduces search and location time. Christ (1975) notes that when the color of the target is known in advance, color coding may result in as much as a 200 percent improvement in search and location over monochromatic or achromatic displays.

Color coding in search has been compared to various achromatic coding methods (Eriksen, 1952; Hitt, 1961; Smith, Farquhar & Thomas, 1965). In general, color is superior to size, shape or brightness coding (Christ, 1975; Eriksen & Hake, 1955; Kanarick & Petersen, 1971). Baker, Morris, and Steedman (1960) demonstrated that color produced better search performance than any other code.

Several studies conclude that color is a more effective alerting cue than size or shape. Smith and Thomas (1964) required observers to search for and count targets of different shapes and colors. The shapes were five geometric forms, five military symbols, and five aircraft silhouettes in green, blue, white, red, and yellow. Test fields consisted of 20, 60, or 100 such shapes. Searching for and counting targets of a specified color was found to be much faster and more accurate than counting targets by shape.

Williams (1966) examined eye movement patterns during search in order to determine the relative impact of color, size, and shape on locating a target. Observers were informed of a target's color, size, and shape before each search trial. Williams found that observers tended to fixate on items of the appropriate color more often than on items of the correct shape or size. Thus, color appears to be a useful coding dimension if large amounts of information must be filtered, since the operator's attention is drawn largely to items of the appropriate color.

Eriksen (1952) coded targets in either one dimension or multiple dimensions combining color, form, size, and brightness. Color coding yielded faster search times than form, size or brightness coding. Results also indicated that search with multidimensional cues was not superior to that with a single dimension. To account for these findings, Eriksen (1953) suggested that multidimensional codes in search tasks increase the processing time of irrelevant information. Thus, while multidimensional coding has been shown to improve performance in detection and identification, it increases the time to locate a target in a search task.

Green and Anderson (1956) asked observers to search for two-digit targets in matrices with different numbers of red and green digits. Although they were told the target's color, that information was not necessary for target location. That is, targets could be located solely on the basis of the two-digit

number. The time required to find a target of known color was found to increase with the number of items of like color. However, search time also increased slightly with the number of irrelevant colors displayed. These results were confirmed by Smith (1962). With very low information densities, Cahill and Carter (1976) found that search time did not increase as a function of the number of items of the same color as the target. In displays having only 10 or 20 symbols, as many as nine irrelevant colors could be added with no increase in search time.

Color facilitates search only if the target color is known in advance (e.g., Green & Anderson, 1956; Smith, 1962). In Smith's research, observers searched fields of three-digit numbers appearing in red, green, blue, orange, or white. Observers searched for specific three-digit targets; target color was either known or unknown. Search time through 100 items for targets of a known color took about the same length of time as search through 20 items for a target of an unknown color. When searching for a target of an unknown color, search times on multicolor displays were equivalent to those on monochrome displays. For known color targets, search time increased as a function of the number of symbols of the same color as the target. When the color of the target was not known in advance, search time increased as a function of the total number of symbols on the display.

As one would expect, search times increase as the irrelevant, nontarget colors become more similar to the relevant one (Carter & Carter, 1981; Farmer & Taylor, 1980). Using a search task in which the background items varied in their similarity to the target, Farmer and Taylor (1980) asked observers to search for five different neutral gray patches in backgrounds of colored patches arranged in matrices. Some of the matrices were quite homogeneous, (e.g., consisting of five shades of red) while others were more heterogeneous, involving dissimilar hues. Search times were lowest with dissimilar targets and background, and with relatively homogeneous backgrounds. If a variegated color background was used, search performance was best when the displayed items were structured (that is, arranged in rows).

Carter and Carter (1981) investigated the effect of similarity of target and background color on search times for three-digit numbers. The color differences used were 0 (one color condition), 12, 36, or 228 CIELUV units. Target class size and display density were also varied. Search time decreased as color symbol differences increased, indicating that colors lying closer together in the CIELUV space are confused. Carter (1982) emphasized the importance of minimizing the number of colors used in a display to ensure rapid and predictable search for critical information.

In complex tasks, color provides increased search efficiency as symbol density increases (Cahill & Carter, 1976; Smith 1962). For example, in a study using colored symbols on aircraft combat information displays, Kopala, et al., (1983) observed pilots performing combat maneuvers that allowed little time for scanning the display. The results indicated that color coding reduced response error rate, especially as display density increased from 10 to 20 to 30 items. The pilots were enthusiastic in their acceptance of color for tactical displays.

Cahill and Carter (1976) asked observers to search displays consisting of between 10 and 50 three-digit numbers coded in one to ten colors. Search time increased approximately linearly with display density. For intermediate and high densities, search time decreased as up to about seven colors were added. At the highest display densities (40 and 50 symbols), search was more rapid on displays of four or five colors with ten symbols per color category than on displays of eight and ten colors with five symbols per color category. These results suggest that color is most useful to designate broad information categories, since search took place most rapidly on displays using fewer colors and more items per color category.

Carter and Cahill (1979) examined two empirical models of search. Both models attempted to explain observed search performance based on display density, number of colors used, and the number of items in each color category. The first model assumed that observers fixate only on items of the same color as the target and that search times were therefore dependent only on the number of these items. This model accounted for approximately 50 percent of the variance in search time among different display densities and code sizes. The second model assumed that additional processing time was also needed for items not of the target's color. This model accounted for 84 percent of the variation in search times, thereby providing a more complete explanation of search performance.

Cahill and Carter (1976) empirically validated this relationship between display density and the processing time for colors on the display. For more than six color categories and for display densities greater than 30, search times were increasingly dependent upon the number of symbols which are not of the same color as the target. As the number of colors increases, they are necessarily closer together on the color space and less discriminable. Increasing the number of colors on dense displays requires more eye fixations and processing time for the irrelevant symbology. As the display density increases, the number of colors used should, therefore, be reduced.

Monitoring and Watchkeeping

A monitoring or vigilance task requires sustained attention as well as the ability to discriminate and respond to categories of information which occur infrequently and/or in unpredictable locations. Watchkeeping tasks require monitoring and detection of infrequent events over prolonged periods of time.

Monitoring and watchkeeping performance tends to decline as a function of task duration (Mackworth & Taylor, 1963). This decline in performance has been attributed to changes in visual sensory acuity. Several investigators have tested this hypothesis by measuring sensory thresholds both prior to and during vigilance task performance. For example, McFarland, Holway, and Hurvich (1942) conducted a study in which observers were asked to detect changes in brightness during a 2 to 8 hour monitoring task. A significant decrease in brightness sensitivity was observed, with the greatest decline during the first 60 minutes of the watch.

It is likely that a performance decrement will occur while monitoring high resolution displays over extended periods. However, the practical significance of this must be determined by tests in the operational environment.

In addition to a loss of brightness sensitivity, observers usually report a loss of perceived saturation of color during continuous viewing of a colored symbol or colored area (Hurvich, 1981). The extent to which loss of perceived saturation occurs during prolonged viewing of high resolution displays and the practical significance of this loss are unknown.

Several studies (Jenkins, 1958; Mackworth, 1948; Sipos, Halmiova, Riskova, & Dornic, 1965) have failed to find a significant correlation between visual acuity and monitoring performance over prolonged periods. The absence of an effect here may be due to the intermittent nature of the task employed. When observers monitor video display terminals continuously for 2 to 3 hours, a temporary reduction (of approximately 15 to 20 percent) in acuity has typically been demonstrated (Haider, 1980; Murch, 1983c).

During prolonged watchkeeping, visual discrimination tends to degrade more than cognitive performance (Davies & Tune, 1969). Therefore, watchkeeping performance could be enhanced most readily by facilitating visual discrimination. Reducing the number of colors used on a display or increasing their wavelength separation reduces the decrements in vigilance performance. Increases in chrominance and luminance contrast among symbols and between symbols and their background also tend to improve visual discriminability (McLean, 1965) and, consequently, to reduce long-term decrements in vigilance performance.

Monitoring has been shown to deteriorate more rapidly where visual scanning is required. In one study, Davis (1948) demonstrated that pilots became less organized in their scan of aircraft display panels as flight time increased.

Performance in vigilance tasks can be improved by reducing the need for visual scanning and by removing irrelevant information. To minimize scanning while maximizing the probability of locating information of critical importance, it should be presented in a standardized location on the display. Color, used to code broad categories of information, further reduces the need for extensive visual scanning and reduces the tendency to process irrelevant information.

Cahill and Carter (1976) reported a study in which subjects were asked to search for colored targets on multicolored backgrounds. Results showed that search patterns were disrupted by the presence of multicolored backgrounds. The use of color to draw borders and lines to separate parts of a display also disrupted search patterns.

The use of auditory alerters is highly effective in improving visual signal detection (Pollack & Knoff, 1958) and vigilance (Smith, Lucaccini, & Epstein, 1967). Color may also aid performance in vigilance tasks when it is used to code a master alert signal or to code low probability information. As with an auditory alerter, the additional sensory information of color on a display may aid in maintaining alertness.

In a study by Kopala (1979), pilots "flew" missions in a flight simulator and extracted information from CRT displays during communications and weapons management tasks. One of the tasks was the peripheral monitoring of real-time threat displays under conditions in which color and shape coding were compared to shape coding alone. The joint coding of color and shape significantly reduced response time and error rate in comparison to shape coding alone.

Kanarick and Petersen (1971) conducted a study in which observers monitored rows of digital readout displays, remembering the status of several continuously changing display values. The payoff schedule used rewarded selective attention to particular rows of displays. The observers reported whether the last information presented was a number, a color, or a combination of numbers and colors. Regardless of the importance attached to a row of displays, numeric coding was superior. That is, observers were more likely to remember that a number had been presented than a color. Redundant number and color information did not further enhance performance on this task. Monitoring performance was also found to improve if the display contained several subsets or groups of information rather than one homogeneous array.

Inspection

Inspection tasks performed on a CRT require the critical or detailed examination of data for values which fall outside the range of normal operation. To facilitate the performance of inspection tasks, color offers potential benefits in highlighting important status indicators and display parameters.

Changes in the brightness, hue, or saturation of a color may be used to indicate status or range. Mapping range or status information onto different hues or hue saturations has clear value for facilitating inspection; however, the methods for employing color in this manner are highly task specific.

Dynamic hue shading must be approached with caution. Abbott (1979) determined that shading of monochrome data resulted in interpretation problems in aircraft cockpit CRT displays.

Surveying

In survey tasks, displays are examined to provide an overview or evaluation of a general situation or event. In this case, color may be used to aid recognition of information categories or to designate categories of information which require immediate, alternate courses of action. Color may be used to convey important information at a glance, as for example, when it is used to code status indicators or to enhance simple pictorial displays.

While surveying weapons stores management displays aboard fighter aircraft (Aretz, Calhoun, Kopala, Herron, & Reising, 1983) information was displayed to pilots using four different formats: alphanumeric, monochrome pictorial, color pictorial, and alphanumeric-color pictorial. Performance indicated that the alphanumeric format was most efficient. However, pilots preferred using the alphanumeric-color pictorial formats. In response to a questionnaire, several pilots noted the benefits of color for providing information at a glance and for providing a general awareness of the tactical environment.

Higher-Order Cognitive Tasks

Counting

It is well known that color facilitates counting (Christner & Ray, 1961; Hitt, 1961; Lee, 1969; Smith, 1963a, 1963b; Smith, Farquhar & Thomas, 1965; Smith & Thomas, 1964). In a task requiring counting of air traffic control symbols (a combined vector, letter, and 3-digit number), Smith (1963a) found that color coding resulted in a 69 percent reduction in counting

time and 76 percent fewer counting errors. In another study, Smith (1963b) required the counting of overprinted symbols; counting of blue symbols was slower than for other colors.

Counting on the basis of color has also been found to be faster than on the basis of shape (Christner & Ray, 1961; Hitt, 1961; Smith & Thomas, 1964). For instance, Smith and Thomas (1964) measured the speed and accuracy of counting as a function of color and type of symbol (military , aircraft, and geometric shapes). Counting was quickest for colored symbols, followed by military symbol shapes, which were counted only half as fast. Red, white, and yellow items were counted faster than blue and green ones. Counting time and errors increased with density (20, 60, or 100 symbols), as did the superiority of color versus shape coding. The authors recommended that color is especially useful for counting on dense information displays, as long as there are only a few information categories and the symbol sizes are small.

For counting tasks, research comparing the effectiveness of color and numeric coding is equivocal. Hitt (1961) found statistically significant performance differences between numeric and color coding, while Christner and Ray (1961) reported that color coding is superior to shape or numeric information for counting.

<u>Reading</u>

Reading involves the recognition of words in context. The extent to which this can be done effectively is referred to as readability. Clearly, the readability of text on CRTs is dependent upon character size, resolution, and contrast.

When symbol size, symbol/background luminance, and color contrast are matched, satisfactory readability has been observed for most colors of text, except for highly saturated red the shortest wavelengths (blue to purple) (see footnote 1). However, it should be noted that for a given display, it may be difficult to produce equal symbol/background luminance, and color contrast for both desaturated and saturated colors. For example, desaturated yellow on a white background at highest possible luminance does not reach equal color contrast to saturated green on a white background; therefore, acuity and readability of yellow characters will be inferior to that of green.

The National Academy of Science (1983) has noted that reading performance is adequate with most colors, except for highly saturated red and blue. These colors produce greater chromatic aberration than those in the mid-spectrum. However, slightly desaturated reds may be used (Rupp, 1981). There is some evidence that middle wavelength, spectrally mixed colors requiring moderate amounts of visual accommodation

provide the best color for long-term viewing of text.[2] Murch (1983b) suggests that the use of middle wavelength, spectrally mixed colors may reduce the need for changes in accommodation and the attendant fatigue.

While it is of interest to estimate the readability of text in various colors for a given application, readability is largely a function of the particular parameters used: purity, luminance, symbol size, ambient illumination, and wavelength. Even if these parameters are specified exactly, differences in color generation techniques may still produce considerable variation in readability. Thus, human factors testing based on behavioral observations with the operational displays is recommended prior to full scale development.

Complex Information Processing and Decision-Making

For complex task performance, color provides maximum benefit in tasks requiring search under conditions of high workload and high symbol/information density (Krebs, et al., 1978). In complex tasks, color coding is also recommended for information which occurs intermittently or in variable location.

Adams (1978) investigated the use of color for reducing clutter on military maps displayed on CRTs. Experienced military map readers reported that color was effective in reducing CRT display clutter, in highlighting special features, and in enhancing the separation and classification of displayed data. Adams' results suggest that as many as seven colors may be used effectively to reduce display clutter on maps.

Oda (1977) used color to indicate the aging of data on CRT displays used by the tactical coordinator in an S-3A aircraft. Color coding was found to reduce reaction time and significantly improve the accuracy of data interpretation on anti-submarine warfare tactical displays. Oda concluded that color: (1) improved mission effectiveness by enabling the tactical coordinator to stay abreast of the tactical situation; (2) decreased the operator's response to work distractions; and (3) enhanced the effectiveness of inexperienced operators.

Connolly, Spanier, and Champion (1975) assessed the usefulness of penetration phosphor color CRT displays as an aid to performance in air traffic control. In one experiment, observers had to interpret overlapping or overprinted symbology that was either in monochrome or in multiple colors. The results showed that accuracy of interpreting the displayed symbology was at least three times better with color coding than

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[2]Murch, G. M. (December 1984). Personal communication. Beaverton, OR: Tektronix, Inc.

with monochrome displays. When color and alphanumerics were used as redundant codes for altitude information and for future route-of-flight information, color did not improve controller performance in predicting violations of separation rules.

Color coding was deemed to be ineffective in complex tasks with relatively fixed formats, highly legible symbols, and low symbol density (Krebs et al., 1978).

Calhoun and Herron (1981) compared the effectiveness of monochrome and color CRT formats for displaying engine status data in a simulated aircraft cockpit. No significant differences were observed in response time to emergencies for the monochrome versus color CRT formats; however, pilots greatly preferred the use of color. The authors emphasized the need for careful evaluation of proposed color displays within the context of the particular task environment.

A recent survey of color applications to control systems, satellite tracking, image analysis, and air traffic control was performed by MITRE (1984). This survey indicated that color has been used in a number of Navy combat control systems to alert the operator to a changing tactical situation, to differentiate target classes, and to distinguish primary from secondary data. It has also been used to correlate tabular data, such as classification, speed, heading, and track history, with the graphical representation of those data. Recently developed Air Force combat control systems have used color to improve detection and reduce errors, to alert the operator, and to manage a high volume of complex data. The Defense Nuclear Agency has a system that utilizes color to differentiate classes of data on map backgrounds. The Army's Tactical Control Analysis Center also employs color displays. These displays reportedly reduce error and improve detection of targets by a factor of 4 to 1 over monochrome displays. A satellite control system developed by IBM for the Air Force Space and Missile Systems Office utilizes color for text editing (e.g., to differentiate edited from unedited data), to indicate the aging of information, to aid status monitoring, and to distinguish classes of data in telemetry analysis.

Color displays are operational in various image analysis systems in the Army, Navy, Air Force, Defense Mapping Agency, and the Department of the Interior. Typical applications are: (1) to delineate detailed weather data; (2) to display high density information with multiple overlays; (3) to manage high volume data; and (4) to improve feature identification and image spectral depth beyond that possible with monochrome displays.

The Air Traffic Control Digital Simulation Facility developed by the Federal Aviation Administration uses color to differentiate critical information in dense air traffic

environments. Navy and Marine Corps air traffic control systems employ color to highlight aircraft against background and to differentiate targets from background and ships from aircraft.

Psychomotor Tasks

Tracking

Tracking tasks requiring the alignment of a response marker to a moving stimulus, may be classified as either pursuit or compensatory. In pursuit tracking, a target moves and the operator must respond by aligning a marker with the moving target. In compensatory tracking, the operator attempts to hold a moving element stationary, such as, for example, holding the speedometer needle stationary while driving a car (Poulton, 1969).

Wagner (1980) reported a study in which pursuit tracking and monitoring were performed concurrently. The primary task involved tracking, where a joystick was used to keep a cross inside a circle. In the secondary task, which involved monitoring, hostile and unknown symbols appeared on a CRT display and the observer had to flip a switch up or down accordingly. Symbols were coded either by color, shape, color and shape, blink, or blink and shape. The symbol density was either 4, 8, or 12 per display. Results indicated that the coding method did not significantly affect performance on the primary tracking task. Moreover, performance on the monitoring task was insensitive to symbol density and the difficulty of the tracking task.

Luder (1984) performed a comparison study of the relative effectiveness of achromatic versus color coded aircraft cockpit displays on piloting performance. To simulate flying an aircraft, a compensatory tracking task was devised which required almost continuous alignment of a small moving circle within a large stationary circle. As a secondary task, subjects were asked to view a centrally located display, which was either in black and white or in color, and to make periodic judgments concerning the status of the fuel system. The judgments took the form of "true-false" statements to questions requiring either search or identification. In an example of a question requiring search, the subject would hear the statement "There are three valves open" and would respond "true" or "false" based on an evaluation of the display. As an example of a question requiring identification of information from the display, the subject would hear the statement "Valves 2 and 6 are closed" and respond "true" or "false".

On the search task, subjects viewing the color display performed significantly better (requiring an average of 749

milliseconds less to perform the search task) than subjects viewing the monochrome display. On the identification task, there was a slight, but not statistically significant advantage to monochrome displays.

Increases in display density (from 5 to 9 elements) significantly degraded both search and identification performance for monochrome displays, but density did not affect performance on color displays. With monochrome displays, increasing display density was more detrimental to identification than to search. Tracking interfered with the identification task more than with the search task. Subjects viewing color displays performed significantly more accurately in the primary tracking task than subjects viewing monochrome displays. In addition, the authors noted that subjects using the monochrome displays tended to tire more quickly on the tracking task than did subjects using the color displays. The authors concluded that the use of redundant color coding on visual displays in a cockpit may improve flying performance, but that only the most important task information should be color coded, since color tends to dominate other task information.

Other Psychomotor Tasks

Although a literature search was performed to identify studies of the effects of color coding on other types of psychomotor task performance, such as aligning, no empirical studies were found.

FACTORS DETERMINING COLOR DISPLAY EFFECTIVENESS

Character Size, Legibility and Readability

Legibility refers to the identification of a character or group of characters, while reading refers to the recognition and understanding of words in context.

The symbol size requirements to provide adequate legibility in high resolution displays appear to be comparable to those for written documents; i.e., 10-12 point font (IBM, 1984). Although printed material may offer higher resolution, and thereby greater visibility, this is offset by the greater luminance contrast for symbols available on CRT displays.

The most comfortable viewing of video display terminals is achieved for character sizes of 16 to 18 minutes of arc, with minimally acceptable character sizes of approximately 11 to 12 minutes of arc (IBM, 1984).

When displays have adequate resolution and character/background contrast, satisfactory legibility is obtained for characters of a minimum size of 16 minutes of arc. Legibility is not significantly improved for character sizes larger than about 18 minutes of arc (IBM, 1984). In the case in which resolution and contrast are degraded, larger character sizes may be necessary for adequate legibility.

For reading of continuous text on displays that provide adequate resolution and contrast, character sizes should be in the range from 14-22 minutes of arc. Such characters correspond to 8-12 point type when viewed at typical reading distances. The most frequently used character size on displays corresponds to 10 - 12 point type. This size is generally preferred by observers (IBM, 1984).

Figure 1 shows the character sizes needed to maintain images subtending between 14 and 22 minutes of arc as a function of viewing distance.

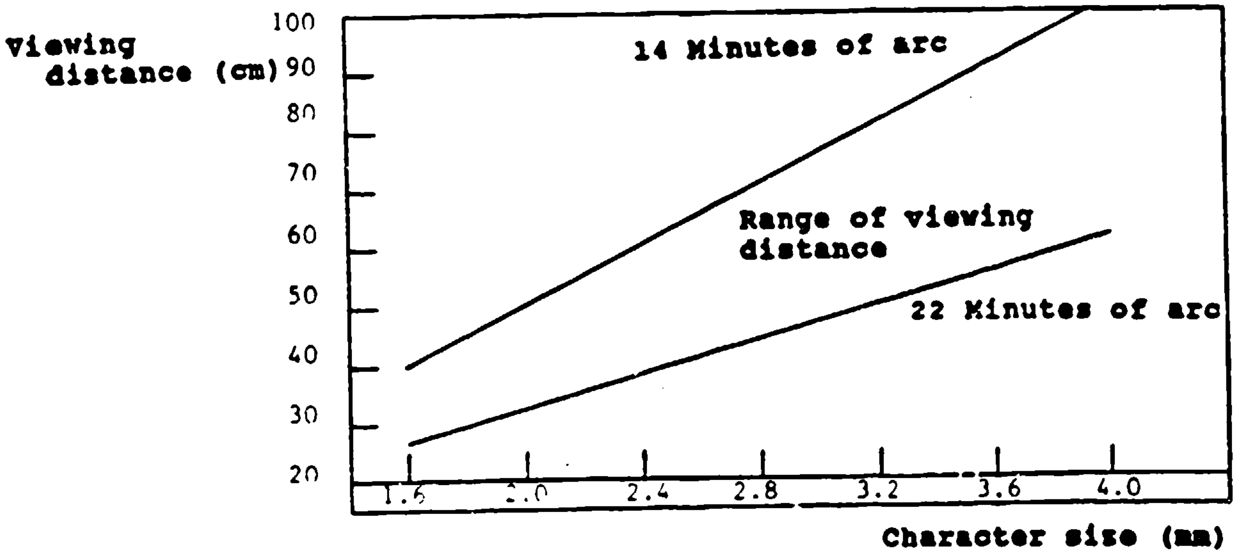

Figure 1. Range of viewing distances for various character sizes for the readability condition in which the characters subtend visual angles between 14 and 22 minutes of arc. (from IBM, 1984, p. 37)

Clauer (1977) studied the effect of character size on the number of reading errors made in a typing task. There were fewer errors for the larger character size (3.43 nanometers

high) than for the smaller size (2.54 nanometers). In a review article, Helander, Billingsley, & Schurick, (1984) stated that character size of 2.54 nanometers is presently accepted as the practical minimum size for characters on a visual display; however, character size was not given as a function of viewing distance.

Kolers, Duchinicky, and Ferguson (1981) recorded eye movements in a study of the effect of display density on reading time. Display density varied as a function of character width (from .50 to .25 degrees of visual angle). The more densely printed characters resulted in fewer but longer eye fixations than the less densely packed characters. This lead to the conclusion that densely packed characters are more efficient for text since they reduce the necessity for saccadic eye movement. A recent publication by IBM (1984) concludes that the reading process is slowed for characters that are too large and which require more fixations per line than smaller characters and recommends a maximum character size for reading of 24 minutes of arc.

A study by Sallio and Morin (cited in Helander, et al., 1984) investigating the readability of fixed versus proportionately spaced text, found that proportionately spaced text resulted in faster reading, fewer eye fixations, and more characters viewed on each fixation. Observers reported that visibility, ease of reading, and contrast were better for the proportionally spaced text.

In a design handbook for graphic displays, Smith (1978) reported that information in the upper right hand quadrant of a display is more salient to an observer, followed by information in the upper left, the lower right, and finally the lower left quadrants.

A complex relationship exists between the variables of luminance contrast and character size as they affect the legibility or readability of characters. This relationship results from the diffraction of light entering the eye by the lens, pupil, and iris. These diffraction effects (due to variations in the focal distance of light of different wavelengths) create blur which reduces retinal image contrast. This loss of contrast, with consequent loss of acuity and legibility is greatest for small symbols (IBM, 1984). To provide equivalent contrast in the retinal image for both small and large characters, luminance contrast should be determined for each symbol size, with smaller symbols having higher luminance.

Adequate chrominance and luminance contrast are necessary to produce high acuity, legibility and readability. However, very high levels of luminance or luminance contrast may reduce viewing comfort as well as the legibility and readability of symbols.

As an example of how this problem has been addressed in cockpit design, where high ambient lighting affects the readability of aircraft displays, photocells have been employed to provide automatic adjustment of display luminance accordingly. The pilot also has manual brightness controls which operate over a limited range to compensate for changes in ambient lighting (see footnote 2).

Lee and Buck (1975) studied the effect of two levels of screen luminance on reading time. The higher luminance (139 cd/m^2) resulted in fewer eye fixations but longer reading times than the lower luminance (88 cd/m^2).

In a study by Bishop and Crook (1961), the identification of targets was poor when the background luminance exceeded that of the target. Additional research (Crook, Hanson, & Weisz, 1954; Howell & Kraft, 1959; Snyder & Maddox, 1978) showed that visual performance increased with symbol/background luminance contrast ratios ranging from 2:1 to 40:1.

Kokoschka (1981/1982) conducted a study to determine the subjectively preferred character/background contrast ratios for the colors: yellow, orange, red, green, blue, violet, and white. Ambient lighting of 300 lux, screen luminance of 100 lux and character sizes of 20 minutes of arc were used in the study. Results showed that optimum contrasts varied between 3:1 (red, purple) to 7:1 (yellow, white). Maximum contrast levels ranged between 4:1 (red, purple) to about 16:1 (yellow to white) and minimum contrast ratios varied between 1.5:1 (red, purple) and 2:1 (yellow, white).

Optimal luminance contrast ratios are determined in part by the character size. In a recent publication (IBM, 1984), the following equation is derived from data presented by Crook et al., (1954) to estimate the contrast modulation requirements for characters smaller than 20 minutes of arc which will provide perceptibility (as opposed to legibility or readability) equal to that of a 20 minute high character with a modulation contrast of 0.3:

$$Cm = 0.3 + 0.06\ (20-S_h),$$

where S_h equals symbol height in minutes of arc. As an example, for the standard character size of 16 to 18 minutes of arc, contrast modulation values of 0.54 and 0.42 will provide perceptibility estimates equal to that of a character of 20 minutes of arc in height at a modulation contrast of 0.3.

The visibility of display symbology depends critically on the luminance contrast between display symbols and background. The required luminance contrast varies as a function of symbol

size, color, absolute luminance of the symbol and background, and level of ambient lighting. Shurtleff (1980) summarized experimental results which indicate that for low absolute luminance (in the range of .01 to 0.1 ft-L) for symbol sizes between 10 and 20 minutes of arc, the minimum contrast ratio should be 18:1 for a high level of identification accuracy. Symbol sizes below 10 minutes of arc will require contrast ratios greater than 18:1. These guidelines are summarized in Table 3.

Table 3

Minimum Contrast Ratios as a Function of Symbol Size and Luminance (Shurtleff, 1980)

Symbol Luminance	Symbol Size	Minimum Contrast Ratio (symbol to background luminance)
.01 to 0.1 ft-L	from 10 to 20 min. of arc	18:1
.01 to 0.1 ft-L	20 min. or greater	5:1
10 to 50 ft-L	10 min. or arc or greater	2:1

Crook, et al., (1954) suggested that symbol luminance of less than 10 ft-L may affect identification accuracy adversely and should be avoided. Faulkner and Murphy (1973) found that threshold acuities do not change very much with increases in symbol luminance from 10 ft-L up to 1000 ft-L. Shurtleff (1980) recommends that displays achieve a minimum symbol luminance of 10 ft-L and that for most displays a maximum symbol luminance of 20 ft-L is sufficient.

It is important to note that equal contrast ratios between symbols and backgrounds do not necessarily result in equal perceptibility or legibility. The absolute luminance of the symbol, the symbol size and resolution, as well as the luminance contrast ratios are determinants of perceptibility or legibility.

In addition to character size, the demands of the task are also important in determining optimal contrast ratios. Thus, recent sources (Helander, et al., 1984; IBM, 1984) estimate that contrast ratios of 3 to 1 are often sufficient for slow paced tasks. If the task requires rapid and accurate perception of characters, contrast ratios of 20:1 (with modulation contrasts (Cm) of 0.9 or more) are recommended. For tasks that require accuracy, but not necessarily speed, Cm should be at least 0.8. For continuous reading of text, the recommended Cm is at least 0.75. For less demanding reading tasks, the minimum Cm is 0.5.

Dark vs. Light Character Displays

There is current debate concerning the relative merits of dark character/light background versus light character/dark background displays.[3]

The important issues regarding these displays involve differences in: (1) relative luminance of the display; (2) display reflectivity; (3) apparent flicker; (4) the relative demands for shifting from printed documents to display viewing, and vice versa; (5) the accommodation response of the pupil, iris, and lens; and (6) the relative legibility and readability of symbology.

In difficult viewing conditions, such as uncontrolled ambient lighting in an aircraft cockpit, there are clear advantages for the use of light characters on black backgrounds. The high contrasts so obtained are necessary to compensate for the loss of color saturation due to high ambient lighting.

For cases in which the image is close to threshold, dark characters on light backgrounds provide greater visibility than light characters on dark backgrounds (IBM, 1984). However, this condition has little practical significance for the design of displays, since characters are typically well above threshold levels of visibility.

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[3]Snyder, H. L. (August, 1984). Personal communication. Blacksburg, VA: Virginia Polytechnic Institute and State University, Department of Industrial Engineering and Operations Research, Human Factors Laboratory.

Table 4 (adapted from IBM, 1984) illustrates the differences in light density (average luminance) and contrast obtainable between dark and light character displays.

Table 4

Light Density as a Function of Luminance Contrast and Display Polarity (IBM, 1984, p.30)

Display Polarity	Background Luminance cd/m^2	Character Luminance cd/m^2	Light Density cd/m^2	Contrast Ratio
dark character	100	10	91	10:1
light character	10	100	19	10:1

Thus, for contrast ratios of 10:1, there is a considerable difference in light density between the two displays. High light density is desirable if the image is close to threshold, but it generally does not improve visibility in suprathreshold conditions.

In Table 5, the two displays are assumed to have equal light densities, maintained at 19 cd/m^2. This results in a five-fold increase in contrast ratio for the light character versus dark character display.

Table 5

Luminance Contrast as a Function of Light Density and Display Polarity (IBM, 1984, p. 30)

Display Polarity	Background Luminance	Character Luminance	Light Density	Contrast Ratio
dark character	100	10	19	2:1
light character	10	100	19	10:1

There is some evidence that the reduction in luminance contrast possible with dark character displays reduces visual fatigue (Seppala, 1984). These displays have also been rated higher in viewing comfort (Helander, et al., 1984).

Bauer, Bonacher and Cavonius (1981) studied the effects of display reflectivity on the legibility of dark and light characters. They found that dark letters on a light background produced less reflective glare than light letters on a dark background. Light backgrounds may, however, become sources of direct glare.

Haubner and Kokoschka (1980/1982) evaluated the relative effectiveness of light and dark displays and assessed various methods for reducing screen reflections. Their task required the reporting of discrepancies between pairs of letters that appeared on the video display terminal screen and on a source document. Fewer errors and more rapid task completion times were recorded for dark screens (micromesh, dark etched, and light etched) than for the light screens (anti-reflective spray and no treatment). The micromesh screen was judged to provide best performance. Screens without reflections resulted in better task performance than screens having specular reflections. No statistical analyses were reported.

Isensee and Bennett (1983) demonstrated that display brightness is the most important factor affecting apparent flicker. They found that flicker was less apparent for lower display luminance, higher ambient lighting, and for light character displays. These authors recommend lowering display brightness to reduce flicker.

Helander, Billingsley, and Schurick (1982) have noted several arguments favoring the use of dark character displays in conjunction with printed material. The reduced luminance contrast as well as the reduced requirement for changes in accommodation on dark character displays can be expected to minimize visual fatigue while maximizing readability.

There have been numerous investigations of the legibility or readability of light versus dark character displays. For example, in a study requiring the detection of model tanks (Hilgendorf & Milenski, 1974), more rapid response times were recorded for light targets against a dark background than for dark targets against a light background. Similarly, in a study conducted for the Navy, Wagner (1975) investigated the detection of green, brown, and gray tanks on green or brown terrain; he found superior and faster detection for targets that were lighter than their backgrounds.

Light characters on a dark background do not provide equivalent character visibility to dark characters on a light background. While reverse video provides a useful highlighting capability, it should be used with caution for tactical displays.

In a study conducted for the Army, Barnes (1970) tested the readability of military aircraft instruments having various pointer/background color combinations. The fewest scale reading (legibility) errors occurred for instruments having greatest contrast between pointer and background. Black backgrounds produced fewer errors than white ones.

In another study of the legibility of numbers on circular dials, McLean (1965) found that dial reading was faster for colored digits displayed against a dark background than for colored digits displayed against a light background. However, for black and white displays, better legibility was found for black digits on a white background than for white digits on a black background.

Note that the differences in performance for dark character versus light character displays in these tasks were generally small. In a review article on human factors of video display terminals, Helander, et al. (1984) concluded that more research of higher quality is needed before the critical issues can be resolved and appropriate guidelines can be developed.

Environmental Considerations

Ambient Lighting and Glare

Combat control displays may be located in ambient lighting environments which range from low-level, fixed luminance control room lighting to highly variable lighting conditions as in an aircraft cockpit. The expected range of lighting conditions must be known prior to display design, since it has a significant impact on display visibility and color perception.

Research has indicated that for ambient lighting levels below 0.1 cd/m^2, symbols are seen as achromatic rather than as colored objects (Krebs, et al., 1978). However, as the level of ambient lighting gradually increases up to about 10 cd/m^2, visual acuity and color perception continue to improve. For a wide range in ambient lighting levels (from approximately 10 to 100,000 cd/m^2) visual acuity and color perception remain fairly constant. However, for ambient lighting levels above approximately 100,000 cd/m^2, visual acuity declines due to glare from diffraction effects within the retina (Home, 1983).

Glare and high ambient lighting produce scattered light which results in desaturation of colors. At extremely high levels of ambient lighting, symbols may appear completely desaturated and in fact, achromatic (Laycock, 1982).

The level of ambient lighting at which the perception of color becomes degraded varies as a function of symbol/background size and color (Burnham, et al., 1963).

Even though acuity remains unaffected by high levels of ambient lighting (up to approximately 100,000 cd/m^2) visual discomfort due to glare occurs prior to this level and may adversely affect task performance. Above 100,000 cd/m^2, substantially reduced acuity from scattered light within the eye occurs, along with the risk of retinal damage.

A distinction is made between direct and reflected glare. Direct glare is produced by a light source within the visual field. Reflected glare is light incident from a polished surface. Both types of glare reduce symbol/background contrast on the display surface.

Much of the research concerning the effects of high ambient lighting on the perception of color on self-luminous CRT displays has been conducted in aircraft cockpits and in cockpit simulators, where ambient lighting is highly variable (Laycock, 1982; Laycock & Viveash, 1981; Silverstein & Merrifield, 1981). Results have shown that high ambient lighting decreases the perceived saturation and brightness of colored symbols. For

CRTs under high ambient lighting, greatest reduction in color discriminability takes place for low luminance colors (see footnote 1). However, increasing the display symbol brightness and the symbol and background contrast are very effective techniques in compensating for the desaturation and loss of visibility due to high ambient lighting (Brown & Mueller, 1965; Silverstein & Merrifield, 1981).

Under high ambient lighting, certain colors become desaturated more quickly than others, and these colors must be coded at higher luminance levels. For example, under high ambient lighting, green and yellow must be of higher luminance than red to be of comparable visibility (Tyte, Wharf, & Ellis, 1975). For equal visibility under very high lighting it is necessary to code green symbols at approximately three times the luminance of red symbols (Ellis, Burrell, Wharf, & Hawkins, 1975).

Research findings support the use of low levels of illumination in control rooms having video display terminals (Helander, et al., 1984; Snyder & Maddox, 1978). Under low ambient lighting there are fewer interfering reflections, and character legibility is generally increased (Helander, et al., 1984).

Snyder and Maddox (1978) suggest that control room lighting of 100 lux or less (measured on a horizontal surface at the workplace) is adequate for viewing video display terminals. However, lighting levels below 100 lux may result in reduced visibility for controls and reduced visual communication between co-workers (Helander, et al., 1984).

Home (1983) suggested that for maximum visual acuity, the general level of white ambient light should be similar to that used on the display.

If the task to be performed includes reading a printed document, then ambient lighting of 200 - 300 lux is usually suggested (Kokoschka & Bodmann, 1978/1982a, 1980/1982b). Use of a spotlight to view printed documents reduces the requirement for ambient illumination to less than 200 lux. In general, the use of adjustable room illumination is strongly recommended (Helander, et al., 1984).

Kokoschka and Bodman (1980/1982b) investigated subjective preferences for luminance contrast between symbols and background as a function of ambient lighting. Subjects preferred ambient illumination of 200 to 300 lux at the workstation, with a 2:1 ratio of direct to indirect lighting. Character/background luminance ratios between 10:1 and 5:1 were preferred, depending upon screen luminance levels. Subjects preferred character luminance between 75 and 105 cd/m^2,

depending upon the screen luminance and ambient lighting levels. An earlier study (Kokoschka & Bodman, 1978/1982a) employed ambient lighting of 300 lux and reported subjective preference for screen luminance of 40 cd/m^2 and character/background contrast ratios of 10:1.

Under very low levels of ambient lighting (below approximately 10 cd/m^2), acuity is reduced. As the pupils apertures enlarge, light becomes more diffuse over the entire retina, increasing the degree of spherical and chromatic aberration. Light of shorter wavelength may be focused prior to reaching the retina. This myopic condition, occurring under low levels of illumination, has been attributed to both diffraction errors (Koomen, Tousey, & Scolnik, 1949) and to difficulties in accommodation (Otero, 1951).

Under very low ambient lighting (below approximately .1 cd/m^2), the eye becomes more sensitive to the shorter wavelengths, and blues are detected much more rapidly than reds (Krebs, et. al., 1978). However, acuity for blue symbols is relatively poor, since the shorter wavelengths are diffracted more and may be focused prior to reaching the retina (Duke-Elder, 1946). Under low levels of ambient illumination (below 0.1 ft-L), most errors in color identification take place for reds of low saturation (Feallock, et al., 1966).

<u>Chromatic Illumination</u>

Symbols appearing under strong chromatic illumination lose saturation in comparison to symbols in daylight (Graham, 1965). However, CRT display symbols are self-luminous and this mitigates the effects of chromatic illumination. It is difficult to predict the effects of chromatic illumination on the color perception of display symbology. The effects depend on various factors, such as luminance, luminance contrast, and saturation of the colors employed. Therefore, if chromatic illumination is to be used, it should be tested in the work environment. Kinney, Neri, Mercado, & Ryan (1983) compared performance on a sonar task under red, white, and blue illumination. There were no differences in performance after one hour but visual fatigue occurred in hyperopes (far-sighted, older individuals) under red lighting.

Luria and Kobus (1984) demonstrated the utility of low level white light (.5 ft-L) as a replacement for red light, which is currently used in submarine compartments. In this study, low level white lighting required an increase of 1 to 2 minutes in the time necessary for dark adaptation in comparison to low level red.

Individual Considerations

Population Differences

There are a variety of color deficiencies which affect about 8 percent of the male population, and about 0.6 percent of the female population (Hsia & Graham, 1965).

The normal eye responds to wavelengths of various colors by means of light sensitive chemicals, known as cone photopigments. These three photopigments are maximally sensitive to wavelengths of 445, 535, and 575 nanometers, respectively, although each type of photopigment responds over a wide range of wavelengths. Most color deficiencies are mild and are ones in which the response functions of the photopigments are shifted, resulting in a reduced ability to distinguish small differences between colors. Persons with this type of color deficiency are most likely to confuse colors under dim lights (Bailey, 1982).

Another common form of color deficiency results from a lack of red or green photopigments in the receptors. In one condition, protanopia, individuals are relatively insensitive to spectral wavelengths exceeding 585 nanometers (Rupp, 1981). In this case the reds generally appear very dark. In another form of red color deficiency, deuteranopia, individuals are sensitive to the entire visible spectrum, but confuse colors with wavelengths longer than approximately 530 nanometers (Home, 1983).

In a relatively rare color deficiency, tritanopia, individuals have approximately normal spectral sensitivity, but confuse colors from the green to the blue end of the spectrum (Home, 1983). In extremely rare cases, the blue photopigment is missing.

Obviously, operators using color displays must be screened for color deficiencies. Current color vision tests may not be adequate to detect very mild color deficiencies (Neil, 1979). Since mildly colorblind persons may perform tasks using color displays, certain color boundaries must be restricted to prevent characteristic confusions (Halsey, 1959). A 1977 seminar of the French Society of Ergonomics (cited in Rupp, 1981) resulted in recommendations against the use of red above 585 nanometers for display coding purposes, since protanopes are relatively insensitive above this wavelength.

As noted earlier, there are wide individual differences in color naming. Halsey (1959) found that for colored signal lights, blues were frequently called purple, whites were frequently called yellow, and purples were often called red. Fewest individual differences in naming occurred for greens.

Visual acuity deteriorates with age. In a normal individual, visual acuity is estimated to decline by a factor of 25 percent between the ages of 20 and 60. Older persons are more sensitive to glare. With increasing age, the humour of the eye becomes more opaque, resulting in increased light scattering and reduced contrast sensitivity (Cakir, et al., 1980). With advancing age, there is also reduced ability to discriminate among colors. It appears that color perception deteriorates more rapidly for some colors than for others. Burnham, et al. (1963) noted that color discrimination losses are greater for the shorter wavelengths. This effect is hypothesized to be due to changes in ocular pigmentation.

Visual Fatigue

Visual fatigue and eyestrain from intensive viewing of video display terminals arises in part from difficulties in accommodation due to luminance contrast between the display and the surrounding work area, differences in the requirement for accommodation to light of different colors, and to the amount of time spent on the task.

Research in the Netherlands (Kalsbeek, Posma, Bosman, & Umbach, 1983) measured changes in acuity over 2 or 3 hours for operators performing search tasks on video display terminals. During this time, information changed every 15 seconds. Performance was compared with the same task performed using printed information and for a non-related typewriting task. There was a small but very reliable temporary (15 minutes) decline in visual acuity after performance on the video display terminal and on the typing task. There was no corresponding reduction in acuity after performance of the search task using printed information.

Isensee (1982) correlated changes in the level of ambient lighting with subjects' ratings of glare discomfort. Reported glare discomfort was minimized for low to moderate ambient light (approximately 65 cd/m^2). Glare discomfort ratings increased considerably under high ambient lighting levels (in excess of 420 lux) and under low display luminance (10 cd/m^2).

There is some evidence that the reduction in luminance contrast possible with dark character displays will reduce visual fatigue (Helander, et al., 1984). In a study by Seppala (1975) (cited in Helander, et al., 1984) subjects reported more eyestrain and headaches after 3 hours of reading light character microfiche as opposed to dark character microfiche.

Relative to broad band white light and without an accommodative response by the eye, red light focuses behind the retina. The shorter wavelength (blue) light at the same distance from the retina focuses prior to reaching it. The

accommodative response of the eye serves to bring images to focus on the retina, with red light resulting in a greater requirement for accommodation than the shorter wavelength blue light (Charman & Tucker, 1978). Bedford and Wyszecki (1947) used green, red, and blue light located at a distance of 50 cm. The requirement for accommodation to green light (at 545 nanometers) was intermediate, requiring a refractive state of 1.8 diopters, in comparison to red light (644 namometers) at 2.3 diopters and blue light (450namometers) at 1.0 diopters. Murch (1983a) determined that broadband desaturated colors produced on 3 phosphor CRTs result in decreased focusing requirements in comparison to primary narrow-band red and blue light. The accommodation response (focusing of the lens, iris, and pupil) to narrow-band green was most similar to that for the broadband desaturated colors: white, magenta, cyan, and yellow.

Murch (1983a) concluded that an eye accommodated at 2.0 diopters would perceive all colors in focus except narrow-band blue. However, the eye accommodated to red at 2.3 diopters would require changes in focus for high acuity to green or blue.

The requirement to view video display terminals for long periods of time may lead to difficulties in accommodation (or inability to focus images clearly). Murch (1983b) found greater difficulty in accommodation to viewing display terminals in comparison to viewing printed material.

The amount of accommodation (focusing of the lens, iris, and pupil) required to focus an object is dependent upon the wavelength of the illumination. Murch (1983a) suggested that the use of desaturated colors may reduce the requirement for changes in accommodation as well as the attendant fatigue.

Color Preferences

The subjective preferences for color versus black and white displays is well documented (Beyer, Schenk, & Zietlow, 1971/1973; Chase, 1976; Tullis, 1980). For aircraft cockpit displays, color coding is preferred for symbols to distinguish weather or terrain from other categories of information (Hart & Wempe, 1979).

Burnham, et al., (1963) reviewed 31 cross-cultural studies of color preference. A large majority of the respondents chose blue or red as their most favorite color and orange or yellow as their least favorite color. In a color preference study employing 20 subjects, Guilford and Smith, (1959) found that the brighter and more saturated colors are preferred. Butler and McKemie (1974) demonstrated that colors having a similar aspect, such as equal levels of saturation, are more likely to be perceived as harmonious. Fromme (1984) found that observers selected the colors red, green, and cyan as choices for layers one, two, and three of a multi-layer circuit board.

In the absence of experimental evidence to recommend the use of one color over another, subjective preference may be used to determine color selection.

RECOMMENDATIONS

Uses of Color

As a general guideline, color should be used to:

1. Designate and standardize broad categories of information
2. Reduce search and location time
3. Provide multidimensional redundant codes
4. Cope with high information densities
5. Highlight important or low probability information
6. Reinforce conventional meanings (red for alert, etc.)
7. Enhance pictorial realism
8. Improve feature extraction capability
9. Increase salience of intensity variations
10. Highlight or reinforce geometric cues

Misuses of Color

Color should not be used:

1. To draw borders and lines between display segments
2. To designate irrelevant information
3. When it distracts the operator or induces irrelevant processing
4. Without careful analysis of the user's tasks
5. Simply for appearance or aesthetic value

To avoid misusing color, it is recommended that:

1. Areas of the display be delineated by spatial separation

2. Essential borders be defined by a color which is similar to the surround

3. Luminance levels (bright and dim) be used in place of additional colors. Bright levels may be used to highlight new or important information or selected modes. Dim levels may be used to define areas of the display or unselected modes.

Problem of Selecting Standard Colors

Ideally a list of colors for a given application might be recommended along with their exact chromaticities and luminances. However, a number of problems exist with respect to accomplishing this goal:

1. There is general agreement that the CIE chromaticity system offers a more appropriate description of color on self-luminous displays than other chromaticity systems currently in use. However, Silverstein and Merrifield (1984) advise that the specification of color in terms of exact chromaticity coordinates should be interprated judiciously, since many factors that influence color perception (such as stimulus size and location, and the influence of other colors in the visual field) were not considered in the original psychophysical color matching experiments used to derive the CIE system. There is also currently no accepted definition of the neutral reference values (y_o, u_o, v_o) of the CIE color difference equations applied to self-luminous displays. A CIE committee now exists to determine neutral reference standards for color difference calculations using self luminous displays. The reader is referred to two excellent sources (Judd & Wyszecki, 1975; Silverstein & Merrifield, 1984) for a full discussion of the CIE chromaticity system and its usage.

2. Color production is display limited. Color formation based on chrominance and luminance specifications will not yield identical results for two different displays. Differences in display color generation techniques, luminous efficiencies (which determine achievable luminous contrast ratios), and such factors as the display environment (ambient lighting and glare) all affect resultant color perception. In addition, nonuniformity of phosphors used on CRTs may result in the production of slightly different colors (i.e., not meeting exact luminance and chrominance specifications) on two otherwise identical displays.

3. The specification of optimal wavelength for color coding is dependent upon the nature of the task and other factors, such as the number of information categories to be coded.

4. The exact chromaticity and luminance specifications for color appropriate for one display environment may not be appropriate for another. For example, chromaticity specifications for use under control room lighting conditions of 20 ft-L may not be optimal for the same display under chromatic illumination, or under the uncontrolled ambient lighting.

Criteria for Selection

Although it is not possible at this time to state the exact chromaticities which are most appropriate to a given display, task, or set of conditions, it is possible to give guidance in the form of criteria important for the selection of specific colors, enabling the designer to avoid arbitrary selections.

Color selection should meet the following criteria. These criteria were developed to apply to all display viewing conditions, ambient lighting, display types and display color generation techniques.

1. The colors should be maximally discriminable to the human observer, i.e., are sufficiently separated in wavelength to eliminate the possibility of confusion.

Draft recommendations for visual display design from a joint committee of the Society for Information Display and the Human Factors Society (see footnote 1) state that colors should be separated by a minimum of 40 CIELUV units. For most important color categories, color separation greater than 40 CIELUV units is desirable.

2. Colors should be maximally discriminable (in terms of adequate chrominance and luminance contrast) from the display background.

Guidelines for the use of color generally specify contrast. A minimum luminance contrast ratio of 5:1 is generally considered adequate to provide good visibility. A minimum ratio of 10:1 is recommended if rapid detection is required. In practice, much higher luminance ratios (20:1 or even 40:1) are acceptable to human observers. There is currently a need for specification of color contrast (such as in CIELUV units) adequate for the performance of common tasks, such as detection and reading of symbology.

3. Colors should be related to the display in accordance with their conventional meanings (such as red for "danger" or "alert").

The highly over-learned response to red, green, and yellow should not be overlooked as a technique to reinforce the meaning of color categories and to improve the accuracy and speed of response in a given situation.

4. Colors should be selected from among those that the display technology produces efficiently.

For example, currently used blue phosphors are only about 50 percent as efficient as red phosphors and about 25 percent as efficient as green phosphors.

5. Colors must be discriminable under the expected range of lighting conditions.

In addition to display luminance, ambient lighting is an extremely important factor affecting the perceptibility and discriminability of colors on a display. Ambient lighting may be considered to be either fixed or variable. If ambient lighting is fixed at levels that are optimal for task performance, it may be appropriate to consider uses of a dark character display (in which darker characters appear on a light background). In this design, operator fatigue may be reduced for long-term task performance. If ambient lighting is variable, maximum discriminability will be produced by saturated colors (except blue and red) which are widely separated in wavelength and viewed against a black background. Similarly, for degraded ambient lighting conditions (i.e. high, low, or chromatic lighting conditions), all colors should be selected at high luminance values, with high luminance and chrominance contrast between symbols and background. Maximal contrast between symbols and background can be achieved by using white or highly saturated, high luminous colors on a black background.

6. Colors should provide high legibility.

Providing that luminance and chrominance contrast ratios between symbols and background are adequate (5:1 or 10:1 for luminance contrast) many colors and backgrounds can produce adequate legibility of characters on shadowmask CRTs. The black and white channel (that is, black characters on white backgrounds and vice versa) can also be very efficient, since high contrast ratios are easily obtained with it.

Since the eye is more efficient in the green to red end of the spectrum, it is recommended that the first colors employed on a display be selected from the middle and long wavelength regions (or be spectrally mixed from these regions). However, it is generally recommended that red wavelengths of less than 585 nanometers (pure red) be employed, especially for reading text, since the longest wavelengths require greatest accommodation (movement of the lens to focus light on the retina) which may result in visual fatigue over time. In addition, several of the most common color deficiencies result in distortion of color perception for the wavelengths above 585 nanometers.

Small details or text should not be coded in blue, since visual acuity for the shorter wavelengths (blue) is poorer than for the medium and longest wavelengths (green to red).

7. Colors should be selected which will not produce display or visual anomalies.

Simultaneous use of highly saturated colors which are widely separated in wavelength (especially highly saturated reds and blues) may result in the perception of spatial separation between the colors, with some colors appearing to recede and others to advance. This effect is frequently distracting to observers.

It is best to avoid using either small neutral colored or yellow symbols appearing on or near large blue areas or small green or red symbols appearing on or near large red or green areas, respectively. These chromatically opponent colors (blue-yellow and red-green) sometimes produce shadows or color shifts for the observer.

To insure the absence of adverse perceptual phenomena, colors selected for a display should be tested and evaluated in the operational setting.

8. Whenever color is used for coding critical items, such as a tactical alert, it should be redundantly coded with an achromatic code, such as alphanumerics or shape.

Symbol Recognition Enhancement

1. For optimal visibility, symbols should be coded at much higher brightness levels than the background. Symbol/background luminance ratios of at least 10:1 are recommended for optimum visibility on multi-colored CRTs. The minimum acceptable symbol/background luminance ratio is 5:1 for character sizes of 18 to 20 minutes of arc.

When coded at equal levels of luminance, some colors will appear to be brighter than others (due to the differential sensitivity of the eye to light of different wavelengths). Symbol to background luminance ratios should ideally be determined for each color used on the display. It is desirable to code very small symbols at higher symbol/background luminance contrast.

2. To eliminate color confusion, it is recommended that only the minimum number of colors be used on the display. These colors should be as widely spaced as possible in wavelength, with a minimum separation of 40 CIELUV units.

3. To provide for adequate symbol legibility and color perception under all lighting conditions, it is recommended that display formats be planned for maximum visibility under the worst viewing conditions anticipated.

Under variable ambient lighting, it is highly desirable to provide the operator with a control to adjust display brightness. In control rooms, the use of adjustable lighting is also recommended for both displays and room lighting. In general, lower levels of ambient lighting (around 100 lux) are best for display character visibility and are preferred by users. If it is necessary to read documents, ambient lighting should be increased to 200 to 300 lux.

4. The symbol size requirements to provide adequate legibility in high resolution displays appear to be comparable to those for written documents, i.e. 10 - 12 point font. This size is generally preferred by observers.

5. The most comfortable viewing of video display terminals is achieved for character sizes of 16 - 18 minutes of arc, with minimally acceptable character sizes of approximately 11 - 12 minutes of arc.

6. For symbols formed in dot-matrix displays, the recommended minimum size is seven dots per row and nine dots per column.

7. For greatest legibility, font styles should be simple and have high resolution. Variable stroke widths or slanted characters should not be used. Upper case letters are clearly preferred.

8. The minimum line width for graphics on a CRT is 3 - 4 minutes of arc. The minimum symbol width-to-height ratio is 2:3.

9. Screen glare should be minimized.

Displays should be positioned to avoid sources of direct glare. Reflected glare may be reduced by etching of the display screen, or by the use of anti-glare plastic coatings, but both methods of glare reduction may reduce display visibility. Display hoods are effective in reducing glare and incident ambient light. The means selected for reducing glare should maintain adequate display luminance contrast and resolution.

10. Chromatic ambient lighting may cause color shifts in display symbology. The interactions of display characteristics and chromatic illumination are complex and unpredictable. If chromatic illumination is to be used, it should be tested in the work environment.

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GLOSSARY

This section (adapted from Banks, Gertman & Petersen, 1982; Silverstein & Merrifield, 1984) contains conversion factors and definitions of important terms used in this report.

Conversion Factors

Illuminance:

1 lux = 0.0929 footcandle (fc)
1 fc = 10.76 lux

Luminance:

1 cd/m^2 = 0.292 ft-L = 0.314 mL
1 ft-L = 3.426 cd/m^2 = 1.076 mL
1 mL = 0.929 ft-L = 3.183 cd/m^2

(cd/m^2 = candela per square meter, or nits; ft-L = footlambert; mL = mililambert)

Type Size

1 point = 0.35 mm = 0.0138 in

Definitions

Accommodation: The dioptric adjustment of the eye to attain maximal sharpness of the retinal image for an object of regard. Focusing of the eye.

Acuity: Ability to resolve or separate detail; a unit equal to the reciprocal of the angular distance, in minutes of arc, of the separation which can just be detected between two objects.

Ambient Illumination: Light from the surroundings, as opposed to light from the display itself.

Brightness: The subjective attribute of any light sensation giving rise to the perception of luminous intensity, including the whole scale of qualities of being bright, light, brilliant, dim, or dark.

Chromatic aberration: Aberration produced by unequal refraction of different wavelengths or colors. The typical manifestation of chromatic aberration in a simple optical system is a colored fringe on the border of an image.

CIE (Commission Internationale de l'Eclairage): An international organization devoted to studying and advancing the art and science of illumination.

CIELUV units: The Commission Internationale de l'Eclairage (CIE) International standards for the specification of color in terms of lightness and a combination of the three spectral primaries: red, green, and blue.

Color: A sensory or perceptual component of visual experience, characterized by the attributes of hue, brightness, and saturation, and usually arising from, or in response to, stimulation of the retina by radiation of wavelengths between about 380 and 760 nm. Sensory components, such as white, gray, and black, which have neither hue nor saturation are properly, but are not always, included with colors.

Dioptre: A standard index of light refraction, the reciprocal of focal length in meters. For example, a refractive state of 1 dioptre indicates a focal length of 100 cm, and a refractive state of 2.30 will correspond to a focal length of 43.

Dominant wavelength: The spectral wavelength which, on proper mixing with white, will match a given sample of color.

Hue: The attribute of color perception denoted by blue, green, yellow, red, purple, etc.

Luminance: A measure of light intensity, the luminous flux per unit of projected area per unit solid angle either leaving or arriving at a surface at a given point and in a given direction. Common units are nits (candela per square meter, or cd/m2), footlamberts (ft-L) and millilamberts.

Luminous flux: The time rate of transfer of radiant energy, evaluated spectrally according to its ability to produce a visual sensation. The common unit is lumens. Also called luminous power.

Primary colors: Any set of colors, such as red, green, and blue, from which other color sensations can be produced by additive mixing. Although it is most common to speak of three primaries, some theorists contend that there are no fewer than four.

Spectral color: A color corresponding to light of a single wavelength. Monochromatic color.

Visible spectrum: The portion of the electromagnetic spectrum which contains wavelengths capable of stimulating the retina, approximately between 380 and 760 nanometers.

Visual angle: The angle formed at the eye by the viewed object. This visual angle is usually stated in terms of "degree of arc" where 1° (degree) = 60' (minutes of arc) and 1' (minute of arc) = 60" (seconds of arc).

Visual angle (for an object less than 10° and perpendicular to the line of sight) is calculated by the following formula:

Visual angle (minutes of arc) = $[(57.3)(60)L]/D$ where L is the size of the object in millimeters measured perpendicular to the line of sight and D is the distance in centimeters from the front of the eye to the object (Bailey, 1982, p. 55).

White: An achromatic color of maximum lightness, representing one limit of a series of grays; the visual sensation typically evoked by radiant energy with the spectral distribution approximating normal daylight.